4185

NATIONAL BUREAU OF STANDARDS REPORT

4185

Engineering Manual for Protective Construction

Part V

Heating and Air Conditioning

of Underground Installations

to
Protective Structures Section
Protective Construction Branch
Office of the Chief of Engineers
Department of the Army

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, *Secretary*

NATIONAL BUREAU OF STANDARDS
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Radio Propagation Engineering. Frequency Utilization Research. Tropospheric Propagation Research.

Radio Standards. High Frequency Standards. Microwave Standards.

- Office of Basic Instrumentation
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Engineering Manual for Protective Construction
Part V
Heating and Air Conditioning
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by

Heating and Air Conditioning Section
Building Technology Division

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NATIONAL BUREAU OF STANDARDS

PROTECTIVE CONSTRUCTION BRANCH

ENGINEERING MANUAL FOR PROTECTIVE CONSTRUCTION

PART V

HEATING AND AIR CONDITIONING OF UNDERGROUND INSTALLATIONS

Chapter 1

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Chapter 2

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Chapter 3

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Chapter 4

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System Capacities and Arrangements

References

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Underground Installations: Heating and Air Conditioning

CHAPTER 1

Introduction

1-01 Purpose

The purpose of this manual is to present in a practical and convenient form all useful engineering data and information available on heating and air conditioning of underground installations. This program was initiated by the Corps of Engineers in cooperation with the National Bureau of Standards and included a literature survey, a mathematical analysis of heat transfer to rock, and field investigations conducted in several existing underground installations. The conclusions and recommendations herein are based upon the results of these approaches.

Having responsibility for establishing procedures and criteria for designing underground constructions, the Office of the Chief of Engineers undertook this program of investigation to develop some necessary data that were lacking and to investigate the applicability of commonly accepted materials, equipment and design to underground installations.

The data gathered so far have been correlated into what is considered an acceptable design procedure although the work is expected to be refined and extended by future experience and experiment. As the advantages of underground installations

become more apparent this manual may attain a broad application and it is hoped that information gained in their use will be brought to the attention of this Office in order to supplement any major contribution this manual may make to heating, ventilating and air conditioning.

Military structures, because of the destructiveness of modern means of attack and the possible increased potency of future weapons may be placed in mines or other excavations below ground. Circumstances in these type of installations are usually such that air temperature and humidity must be controlled to maintain conditions within satisfactory limits for occupancy and preservation of equipment, supplies and materials. Structures subject to dampness may have to be air conditioned for storage of perishable goods, hygroscopic materials or critical war material susceptible to deterioration in moist surroundings.

The omission of air conditioning systems in the initial design of military structures built during the war can be attributed in some instances to wartime restrictions imposed on the use of this equipment. However, it has since been realized that controlled air conditions are necessary for efficient work with papers, delicate tools or instruments as well as for material preservation and therefore a variety of heating, ventilating, and air conditioning equipment has been installed in seacoast fortifications and in military structures within the

United States. While for the most part the results have been satisfactory there are cases in which the measures taken either do not meet or greatly exceed the minimum requirements. The principles and phenomena involved are fairly well understood but there has been a lack of data on which to base ~~proper~~ design, and selection of equipment sizes.

1-02 Scope

The scope of this Manual includes system design, capacity selection and application of heating and air conditioning equipment to underground spaces intended for human occupancy, storage space or other use. Underground spaces may be utilized for protective structures, office or tactical administrative use, signal centers, machine or electrical equipment parts production or repair, storage of equipment, munitions, or documents, etc., or storage of food. The heating and air conditioning equipment for underground structures may include steam, hot water or warm air heating systems, mechanical or absorptive-type air conditioning systems, dehumidifiers, heat pumps and cooling towers or other means for disposing of waste heat, etc. There may be need for segregation of the air conditioning system into zones. Auxiliary equipment will include fans, duct work, pumps, piping systems and controls. An underground chamber may or may not have a liner or inner structure, insulated or

uninsulated. Ground water may add to the latent load or condensation on rock may reduce the latent load in air conditioning processes.

Temperature, humidity and other air conditions required in underground installations may not be different from those maintained in surface structures when the purposes are similar but air conditioning processes used and design procedures may be considerably different. The conditions peculiar to underground use are emphasized in this manual and some data and information applicable to any heating and air conditioning problem are included for convenience and completeness.

Underground protective structures can be divided into three broad functional classes based on the use of the space; namely, storage, industrial, and military. The treatment of the space, the air conditions required, and the type of air conditioning equipment installed would be different for the three types of usage.

Underground storage spaces might be used for preserving food above or below freezing temperatures, for general storage of miscellaneous supplies and equipment, or for storage of military material such as explosives, precision machinery, or organic and fibrous materials that are hygroscopic. In such structures accurate control of temperature and humidity to the conditions best suited to the

stored goods would be of primary importance, whereas human comfort and ventilation would be relatively unimportant and there would seldom be any large amounts of heat generated in the structure.

An underground industrial site might be a machine shop, a factory for precision instruments, explosives, or electronic equipment, a foundry or metallurgical plant, a fabrication plant or any one of many other important industrial activities. In such an installation the particular industrial process in use would often determine the capacity of the heating and air conditioning system required and would frequently have an important bearing on the temperature and humidity to be maintained. In some cases there would be a high heat release in the space requiring a high rate of ventilation or continuous air conditioning. Some processes might release toxic gases that would require high ventilation rates. Human occupancy would always be involved but might not be of high density. In installations having processes liberating large quantities of heat, gases, or vapors, conditions under the attack phase might rapidly become critical unless the processes could be stopped quickly.

A military installation might be a communications center, a fortification, an air raid shelter, a staff headquarters, or a research activity. In such structures the human heat load might frequently predominate although the heat release of equipment might also be high in some instances.

Such military sites would often need to remain in operation during attack conditions. Vitiation of the air might become critical during attack under high density occupancy. Greater attention would have to be given to providing adequate facilities for maintaining full working capabilities during abnormal conditions in this type of installation.

Each of the broad classes of usage described and some of the special uses in each class would require a different kind and number of commercial services or utilities, different types of air conditioning and ventilating systems, varying provisions for self-sufficiency under abnormal conditions, and oftentimes different optimum conditions of temperature and humidity under normal conditions.

1-03 Historical Background

Underground installations can be utilized more advantageously now than heretofore chiefly because a variety of heating and air conditioning equipment is readily available and knowledge of its use has increased rapidly in recent years. In the past, underground spaces appear to have been avoided for practical purposes, chiefly on account of dampness or heat and dampness in combination. Few, if any, underground spaces were air conditioned for personnel comfort or efficiency or for the preservation of equipment or material prior to World War II. Some deep mines were cooled by refrigeration but the objective was

to permit survival under conditions of heavy labor at low levels where valuable minerals would be otherwise unattainable.

Early measures taken to prevent dampness within heavy masonry structures included provision of small air passages in the walls through which air circulated as a result of natural draft or convection. They were intended to keep the wall temperatures near to the room air temperatures and thus preclude condensation. However, in many cases the effect was not adequate and the resulting conditions were often unsatisfactory.

It is reported to be the practice in some salt mines to pass the outside air introduced for ventilation through a worked-out portion of the mine. The air, if received hot and humid, is cooled to a degree and dried by the residual salt. In the working portion of the mine the air is warmed by the machinery and lights with a resultant lowering of the relative humidity.

Applications of a similar scheme to underground spaces other than salt mines are also recorded. Air is drawn through unused underground spaces where it is cooled and dried by contact with the rock. Then it is warmed to an acceptable temperature and introduced into the occupied spaces. The relative humidity falls when the air is warmed and thus an unused tunnel or other underground space is a means of air conditioning. Where this process has been employed in the

past, the underground space used for conditioning the air has has usually been large compared to the occupied or conditioned space and the limits of the capacity of an unused tunnel or other space as an air conditioner were not known. It is contemplated that a more exhaustive study of this subject shall be made a part of the present program on underground air conditioning.

Underground spaces were utilized in Norway, Sweden, Germany and Japan during World War II chiefly as manufacturing or processing plants. Much useful information on this subject is contained in a report "Underground Installations, Foreign" (Ref. 3), but the report yields little design data on heating and air conditioning. It appears that air conditioning was not considered justifiable for most underground installation in a majority of these countries under the then prevailing war time conditions. Of the plants surveyed only seven percent had air conditioning and only forty-seven percent had other than natural ventilation. Heating was reported as provided in twenty-seven percent of the plants surveyed.

The paper "The National Gallery in War Time" (Ref. 5) is an account of the underground storage of paintings from the British National Gallery. An existing site was selected that provided space for the whole collection and afforded 200 to 300 feet of rock cover. The initial air conditions were 47F and 95 to 100 percent relative humidity. The underground space,

apparently an old mine, was large so six buildings were erected within it to contain the pictures. Each small building was warmed by means of a forced-circulation system apparently utilizing electric heat. For ventilation, small amounts of air from the space, at 47F and near saturation, were introduced into each building as required. It was found that when the buildings were warmed to 64F the interior relative humidity was near 57 percent which was considered satisfactory for long term storage of the pictures. No cooling means or dehumidifying means was required and no dehumidification other than that provided by the heating system in conjunction with the enclosing, relatively cool chamber.

With this background of information this program was undertaken by the Office of the Chief of Engineers in cooperation with the National Bureau of Standards.

2-04 Structural Arrangements, Definitions

Some features of the structural arrangement of an underground installation affect the size and design of the air conditioning equipment and system. Relevant definitions are as follows:

Bare Chamber: An underground chamber with no covering on the rock walls or ceiling that will appreciably affect heat transfer; walls painted to improve illumination of the chamber are considered bare from the heat transfer standpoint. A chamber with a concrete floor poured on the underlying rock is considered a bare chamber.

Lined Chamber: An underground chamber with a wall covering of concrete or another material in contact with the rock walls and ceiling. The wall covering, or liner, may have sufficient thermal resistance to affect heat transfer from the chamber to the rock. Some liners may consist of insulating or acoustical material and may contain a vapor barrier.

Internal Structure: A building or enclosure erected within an underground chamber to house equipment or facilities. The internal structure reduces the heat transfer from the occupied space to the rock (Section 4-05) and influences the dehumidification load (Section 3-05).

Annular Space: The space around an internal structure, between it and the rock walls, floor and ceiling of an underground chamber.

1-05 Operating Conditions

An underground installation must be heated or air conditioned to accommodate the activity under various operating conditions. Some of the probable operating conditions of an underground space are as follows:

Stand-By: Facility ready for normal operation at short notice; may be occupied by a skeleton force for maintenance; air conditioned for maintenance of equipment and furniture.

Normal Operation, Maximum Capacity: Facility operating at full or design capacity; occupied by full complement of personnel; air conditioned for personnel efficiency (Section 2-04) and as required for operation of equipment.

Normal Operation, Partial Capacity: Facility operating at less than full capacity as when full output is not required; air conditioned for personnel efficiency and equipment operation in occupied parts; air conditioned for equipment maintenance in other parts.

Alert Conditions: Occupancy and activity the same as Normal Operation; except for adjustments made in anticipation of attack.

Attack Condition: Occupancy and activity the same as Normal Operation except for alterations necessitated by attack.

Post Attack: Normal Operation to the extent permitted by damage due to attack.

Disaster Condition: Outside services including power, water supply, and possibly sewage disposal system cut off and outside air supply greatly reduced or cut off; personnel and facilities dependent on stored water, food and emergency power sources; air revivification essential for survival of personnel.

1-06 Symbols

Symbols utilized in this work are as follows:

A = Area, ft^2; A_1, A_2 and A_3 for floor, walls and ceiling respectively; A' for internal structure; A for exposed rock, A_w for wetted surface

a = Radius, ft; a_1 for equivalent cylinder, a_2 for equivalent sphere

B = Mathematical quantity for use in section 4-05

C = Mathematical quantity for use in section 4-05

C = Conductance, Btu $hr^{-1}ft^{-2}F^{-1}$

c = Specific heat, Btu $lb^{-1}F^{-1}$; c' for water

F = Mathematical quantity for use in sections of chapter 4.

F = Degrees Fahrenheit or temperature difference, F.

f = Function of; depends upon

G - Mathematical quantity for use in equation 4-06

h = Surface heat transfer coefficient, Btu $hr^{-1}ft^{-2}F^{-1}$

K = Thermal conductivity, Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$

k = Thermal conductivity, Btu $hr^{-1}ft^{-2}(F/in.)^{-1}$

L = Length, ft; distance from entrance of tunnel section 4-05

L = Length, ft, of wetted area, figure 4-12

M = Mass, lbs; M' = mass (lbs) of water per foot of tunnel or reservoir

m = Length, ft. of underground space

N = Mathematical quantity for use with equation 4-06

n = Width, ft. of underground space.

P_w = Water pressure, lb in.$^{-2}$

p = Pressure, lb in.$^{-2}$; p_s = vapor pressure, water on a surface; p_a, vapor pressure, water vapor mixed with air

Q = Heat transferred or absorbed, Btu

R = Ratio, for use with equation 4-05

q = Heat transfer rate, Btu hr^{-1}ft^{-2}, from air to rock; q' for constant rate

q_1 = Heat absorption per foot of length of reservoir, Btu hr^{-1}ft^{-1}

q_2 = Heat absorption of reservoir, Btu hr^{-1}

s = Height, ft, of underground chamber

T = Temperature, F; T_o for outside air; T_p for initial rock; T_s for rock surface; T_i for inside air design temperature, T_a for annular space

t = Time, hours

θ = Temperature increase, degrees F; $θ_s$ for rock surface $θ_i$ for inside air; $θ_L$ for air at distance L from tunnel entrance; $θ_w$ for water in a reservoir

U = Heat transmittance, Btu hr^{-1}ft^{-2}F^{-1}, for a wall or other heat barrier

U' = Heat transfer coefficient, Btu hr^{-1}ft^{2}F^{-1}, from air in occupied space to surrounding rock; for no internal structure, U' = h

V = Velocity, ft hr^{-1}

V = Mathematical quantity for use with figures 4-1 and 4-2

W = Water flow rate, lb hr^{-1}; W' for evaporation of water

w = Angular velocity

Z = Mathematical quantity for use in section 4-05

ρ = Density, lb ft^{-3}; ρ' for water

1-07 Data Forms

Some forms for recording data and to serve as work sheets are suggested as follows:

Form A - Design Information

B - Heating and Cooling Loads

C - Rock Heat Absorption, Warm-up

D - Rock Heat Absorption, Normal Operation

E - Heat Absorption Capacity of a Reservoir

F - Cooling or Heating of air in Tunnels or Shafts

These forms are expected to be improved as indicated by future use and experience. Extra copies should be obtained or provided as required for different problems.

FORM A

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN DATA AND COMPUTATIONS

DESIGN INFORMATION DATE:

LOCATION: ____________________

PURPOSE: ____________________

DIMENSIONS, ROCK CHAMBERS

LENGTH, M = FT; WIDTH, N = FT; HEIGHT, S= FT

FLOOR AREA, A'= FT^2; INTERNAL AREA, A= FT^2; VOLUME = FT^3

REMARKS: ____________________

DIMENSIONS, INTERNAL STRUCTURE (IF USED)

LENGTH = FT; WIDTH = FT; HEIGHT =

FLOOR AREA = FT^2; INTERNAL AREA = FT^2; VOLUME = FT^3

DEPTH OF OVER BURDEN FT

GEOLOGICAL FORMATION ____________________

GROUND WATER CONDITION ____________________

CLIMATE	WINTER		SUMMER	
	MIN.	DES.	MAX.	DES
DB, F				
WB, F				
RH, %				

RAIN FALL, INS.

SNOW, INS.

ROCK TEMPERATURE, INITIAL UNDISTURBED, F

REQUIRED INSIDE AIR CONDITION F; %RH

PERSONNEL PERSONS

PREPARED BY:

FORM B

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN

HEATING & COOLING LOADS

	SENSIBLE	LATENT
HEAT GAIN BTU HR^{-1}		
PERSONNEL, PERSONS x 270 (SENS.); x 230 (LAT)		
LIGHTS; KW x 3415		
ELECTRIC MOTORS KW x 3415		
COOKING EQUIPMENT		
OTHER EQUIPMENT		
TOTAL INTERNAL LOAD		
FRESH AIR SUPPLY, SUMMER		
TOTAL COOLING LOAD		
FRESH AIR SUPPLY, WINTER		
CFM x 1.08 $(\theta_i - \theta_L)$ =		

TIME FROM START, HOURS	2000	5000	10,000	20,000
ROCK HT. ABS. BTU HR^{-1}				
TOTAL COOLING LOAD				
NET COOLING LOAD				
TOTAL HEATING LOAD				

FORM C

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN DATA AND COMPUTATIONS

HEAT ABSORPTION BY ROCK SURROUNDING AN UNDERGROUND INSTALLATION; WARM-UP PERIOD

CHAMBER DIMENSION, FT.: LENGTH, M= ; WIDTH, N= ; HEIGHT, S=

INTERNAL AREA, EQ. 4-01, $A = 2\,(MN + MS + NS)$ = FT^2

EQUIV. CYL, RADIUS, EQ. 4-02, $a_1 = A/2\pi M$ = FT

EQUIV SPHERE, RADIUS, EQ. 4-03, $a_2 = \sqrt{A/4\pi}$ = FT

V_1/V (CYLINDER)* FIG. 4-1 =

V_2/V (SPHERE)* FIG. 4-2 =

ROCK: DENSITY, ρ = ; CONDUCTIVITY K** = ; SP.HEAT, C= ; TEMP., T_R= F

$\theta_1 = T_1 - T_R$ = F; U' (SEE 4-08) =

FIND RELATION BETWEEN WARM-UP TIME (t, HOURS) AND HEAT INPUT, q' (BTU. $HR^{-1}FT^{-2}$) BY MEANS OF EQUATION 4-04.

$F = Kt/\rho c a^2$ (USE a_1 FOR CYLINDRICAL CASE, a_2 FOR SPHERE) =

FIND f (F) = , FROM FIG. 4-3 (CYL), IN 4-4 (SPHERE).

SOLVE FOR HEAT REQD FOR WARM-UP PERIOD WITH THE EQUATION

$$q' = \frac{K\theta_1}{a f(F) + K/U'}, \quad \text{BTU } HR^{-1}FT^{-2} =$$

ROCK HEAT ABSORPTION, TOTAL PER HOUR, Aq' = BTU HR^{-1}

*IF V_1/V EXCEEDS V_2/V, UTILIZE CYLINDRICAL CASE

*IF V_2/V EXCEEDS V_1/V, UTILIZE SPHERICAL CASE

**BTU PER HOUR FOR ONE SQUARE FOOT AND FOR A TEMPERATURE GRADIENT OF ONE DEG F PER FOOT OF THICKNESS.

FORM D

HEAT ABSORPTION BY ROCK SURROUNDING AN UNDERGROUND INSTALLATION; NORMAL OPERATION

PROPERTIES OF ROCK:

CONDUCTIVITY, K= ; DENSITY, ρ = ; SP. HEAT, C=

PROPERTIES OF STRUCTURE:

HEAT TRANS. COEF. AIR TO ROCK, U'= ; RADIUS OF EQUIV. CYL. OR SPHERE, a = FT

MAINTAIN AIR TEMP. , T_1, ABOVE INITIAL TEMP. T_R; $T_1 - T_R = \theta_1$

ROCK SURFACE TEMP., T_S, USE ABOVE INITIAL TEMP., T ; $T_S - T_R = \theta_S$ AT ANY INSTANT.

WITH EQUATION 4-05, SOLVE FOR ROCK HEAT ABSORPTION,

q = BTU $HR^{-1} FT^{-2}$

$N = aU'/K$ = ; R (FIG 4-1 OR 4-2) =

TIME FROM START, HOURS, t	2000	5000	10,000	20,000
$F = Kt/\rho c a^2$				
$\theta_S/\theta_1 = f(F,N)$; EQ. 4-06				
$q = U'\theta_1 (1 - \theta_S/\theta_1)/R$				
TOTAL HEAT ABSORBED = Aq PER HOUR				

FORM E

HEAT ABSORPTION OF AN UNDERGROUND RESERVOIR (PIPE OR TUNNEL) FILLED WITH WATER

PERMISSIBLE TEMP. RISE OF WATER, $\theta_W =$ DEG F IN TIME, $t =$ HOURS FOR

A HEAT ABSORPTION OF $q_2 =$ BTU HR^{-1}

PROPERTIES OF ROCK:

THERMAL CONDUCTIVITY, $K =$; DENSITY, $\rho =$; SP. HEAT, $C =$

PROPERTIES OF WATER:

DENSITY, $\rho' = 62.4$; SP. HEAT, $C' = 1.0$

DIMENSIONS OF RESERVOIR (FOR RECTANGULAR CROSS-SECTIONS)

WIDTH, $N =$ FT.; HEIGHT, $S =$ FT.; LENGTH, $L =$ FT.

RADIUS OF EQUIVALENT CYLINDER, $a = (S + N)/\pi =$ FT.

IN EQUATION 4-08, $\theta K/q_1 = F\,(F, G)$

$$F = Kt/\rho c a^2 =$$

$$G = 2\rho c/\rho' c' =$$

VALUES OF $F\,(F, G)$ ARE GIVEN BY THE CURVES ON FIGURE 4-7

THEN $\theta K/q_1 = F\,(F, G) =$

$q_1 =$ BTU $HR^{-1}FT^{-1}$

REQUIRED LENGTH, $L = q_2/q_1 =$ FT.

VOLUME, $= SNL =$ $FT.^3$

COOLING OR HEATING OF AIR IN TUNNELS (OR SHAFTS)
CONTINUOUS AIR FLOW, ANNUAL WEATHER CYCLE

DIMENSIONS OF TUNNEL

LENGTH L = FT; WIDTH N = FT; HEIGHT, S = FT

PERIMETER, P, $2(N + S)$ = FT; C.S. AREA, NS = FT^2

HYDRAULIC RADIUS, $2NS/P = a$ = FT

PROPERTIES OF AIR ENTERING TUNNEL FROM OUTSIDE

MEAN ANNUAL TEMP. = INITIAL ROCK TEMP, T_R = F

TEMP. DIFF., OUTSIDE AIR AND MEAN ANNUAL TEMP., θ_0 = F

MAX. VALUE OF θ_0, θ_0' = F

AIR VELOCITY IN TUNNEL V = FT HR^{-1}

PROPERTIES OF ROCK

CONDUCTIVITY, K = ; DENSITY, ρ = ; SP. HEAT, C =

COEF. OF HEAT TRANS. AIR TO ROCK, h = ; DIFFUSIVITY, α =

CONSTANTS COMPUTED FROM ABOVE DATE FOR USE IN EQUATIONS ON PAGE 2

w = 0.000717 RADIANS PER HOUR

$b = h/K\sqrt{\alpha/w}$ =

$z = a\sqrt{w/\alpha}$ =

$C' = hL/Va$ =

$C = F_1(b, z)$ FIG. 4-8 =

$B = F_2(b, z)$ FIG. 4-9 =

$C'C$ =

$C'B + wL/V$ =

SOLUTION OF EQUATION FOR TUNNEL HEAT TRANSFER

MAXIMUM AND MINIMUM TEMP. AT POINT L IN A TUNNEL, (EQ. 4-11)

$$\theta_L' = \pm\, \theta_O'\, e^{-CC'} =$$

$$T_L' = T_R + \theta_L' \quad = \qquad\qquad , \text{ ALSO } T_R - \theta_L' =$$

TEMP. θ_L, IN TUNNEL AT POINT L AT TIME t, (EQ. 4-10)

$$\theta_L = \theta_O'\; e^{-CC'} \cos\,(wt - wL/v - C'B)$$
$$= \_\_\_\_\_\_ \cos\,(wt - \qquad\qquad)$$

OUTSIDE AIR TEMP. θ_O (EQ. 4-09)

$$\theta_O = \theta_O' \cos wt$$

RATE OF HEAT LOSS OR GAIN BY AIR IN TUNNEL AT POINT L AND TIME t, (EQ. 4-12)

$$q = 0.0566\; v\, a^2\, (\theta_O - \theta_L)$$

TEMPERATURES AND HEAT FLOW RATES DURING ANNUAL WEATHER CYCLE

		JUL 15	SEP 15	NOV 15	JAN 15	MAR 15	MAY 15
TIME	HRS	0	1460	2920	4380	5840	7300
wt	RADIANS	0	1.047	2.094	3.142	4.189	5.236
OUTSIDE TEMP,* θ_O	, F	θ_O'=			$-\theta_O'$=		
TEMP. AT L,*							
TEMP DIFF $(\theta_O - \theta_L)$, F							
HEAT LOSS OR GAIN, BTU/HR^{-1}							

*FOR ACTUAL TEMPERATURES, ALGEBRAICALLY ADD THE MEAN ANNUAL TEMP. T_R TO θ_O OR θ_L.

CHAPTER 2

Principles: Design Objectives

2-01 Function of Underground Installations

The design of the heating and air conditioning system for an underground installation depends on the location, function, size and shape. These factors are likely to be established by the agency requiring the space or by some higher authority, on a basis of anticipated needs. Form A is suggested for recording the necessary data.

Underground installations may serve as protective structures for tactical administrative offices or communication centers; as shops or factories producing machine parts, electronic equipment, chemical products or instruments, or as storage space for machine parts, instruments, electronic equipment, food, clothing, munitions or other equipment. Hospital wards as well as domestic facilities including kitchens, lavatories and berthing accommodations may be required in conjunction with any of these other functions.

The heating and air conditioning system must maintain conditions suitable for personnel efficiency (2-04) in working spaces and for material preservation (2-05) in storage spaces as well as shops, offices and other spaces where equipment is utilized. These conditions must be maintained during the standby, normal operating and, so far as possible, during the attack and post attack conditions (2-03). Air conditioning

or revivification of the air must also be considered for a condition of extreme emergency or disaster (2-07).

2-02 Design Criteria and Limitations

The size, shape and depth of cover chosen for an underground installation may be influenced by function. A storage space for clothing, food, etc., may be irregular in shape and have a relatively shallow cover of earth and rock. More important equipment or facilities essential to defense may be installed in deeper workings. The chambers in deeper workings are likely to be long and tunnel-like. The installation may occupy one or several stories and there may or may not be an inner structure (1-04).

Location determines the climate and the geological formation (4-06) that will surround a proposed underground structure. Climate (1-16) in turn, governs the conditions of outside air (4-06) available for ventilation, the prevalence of underground water (4-10), availability of water for equipment cooling (3-12), and the initial earth or rock temperature (4-07).

Floor area and volume of an occupied space depends upon population, function and internal load (2-10)(3-01).

Environmental conditions, in particular temperature, humidity, purity and, to a lesser extent, motion must be selected with reference to personnel efficiency (2-04) or endurance (2-07) and material preservation (2-05).

Outside or fresh air must be supplied except under emergency conditions for personnel (2-06), for engines or boilers (2-08) for kitchen and lavatories (2-09) and for any special processes involved.

Air filters are usually recommended for all air to be passed through conditioning coils, used in engines or to ventilate shops where delicate equipment is stored, made or repaired. Air purifiers are essential for all fresh or outdoor air if maximum security is required (5-10).

The initial temperature (4-07), thermal conductivity and heat capacity of the surrounding rock (4-06) affect the heating and cooling loads in an underground chamber (5-01).

2-03 Air Conditioning Requirements

For design purposes an interior air condition of 75F and 50 percent relative humidity can be assumed in many cases. This condition is within the practicable range attainable with conventional equipment (5-09) and available data show it to be suitable for personnel efficiency (2-04) and for material preservation (2-05) under usual circumstances. In general air conditions for underground installations should be similar to those selected for surface structures utilized for the same or similar purposes. Fresh or outside air supply (2-06) may be reduced since comfort is not always a prime objective. Since infiltration is unlikely in an underground installation, the air supply and exhaust systems must be adequate to handle the

air required at all times.

Air conditions maintained in a space may differ from those assumed for design purposes, as indicated by practical consideration after operations have commenced. Special air conditioners may be required for special purposes, such as storage or work with unusual materials.

3-04 Air Conditions for Personnel Efficiency

Experience has shown that personnel can sustain a considerable range of temperature from about 55 to 85 F without serious loss of efficiency, particularly if the humidity is controlled and is adjusted downward when the temperature increases or vice versa. The condition 75F and 50 percent relative humidity may be assumed for design purposes (3-03) but other conditions in the comfort zone (Ref.1) are also satisfactory for many purposes. The comfort zone is defined as that area on a psychrometric chart for which 50 percent or more of the subjects were found to be comfortable during some tests conducted by the American Society of Heating and Air Conditioning Engineers. The comfort conditions are still under examination and new findings are in prospect, particularly relating to effects of radiation. Changes in design criteria are not likely to be extensive, however, so far as air conditioning underground installations are concerned where convection heating and cooling will predominate. The findings are more likely to result in adjustments to existing data.

The condition 75F and 50 percent relative humidity is warmer than the 68 or 70F often recommended for indoor winter temperature. However, in many occupied spaces, cooling rather than heating will be required due to internal loads and use of the higher temperature reduces the size and load on the cooling equipment. It is common experience that many people are more comfortable at a DB temperature of 75F winter and summer than at a DB temperature of 70F. The condition 75F and 50 percent is safely below the conditions of excessive sweating which can interfere with the performance of instrument makers, draftsmen, typists and others working with papers and office equipment.

Fresh or outside air must be supplied to occupied spaces in proportion to the population (2-44).

2-45 Air Conditions for the Preservation of Materials

Available data indicate that a humidity in the range from 40 to 65 percent is satisfactory for the preservation of most technically useful materials at substantially steady temperature conditions, either in storage or in use as in shops, offices or communication centers.

An important exception is unprotected mild or carbon steel which requires a humidity of 15 percent or below for no damage or 30 percent or below for tolerable damage in 30 months. This means that special low humidity may be required in instrument shops where such steel is worked or stored without oil or rust preventive treatment.

Probably the most comprehensive information now available on the relation between humidity and deterioration of materials are those gathered under the auspices of the U.S. Navy and reported in reference 1. The data in Table 2-1 were extracted from that source.

TABLE 2-1

Humidity Tolerance of Some Materials
for 30 Month Period

Item Damage, Severity	Humidity A*	B*	C*	Nature of Damage
Mild Steel, polished, unprotected	15	30	65	Rust
Steel (Ball Bearings Rust Preventive applied by Manufacturer)		65	90	"
Steel (Ball Bearings heavy Polar Comp.)		65		
Alloy Steel		90		
Galv. Steel		65	90	Tarnish and rust
Brass and Bronze	15/	90/		Tarnish
Aluminum and its alloys		90/		"
Rubber, Plastic, Rayon		90/		Mildew
Flax, Wool, Cotton, Hair				
Leather, Sponge, Hemp.		65	90	"
Sisal, Paper, Wood				
Soap, Bars			90	Disintegration
Tinned Cans (canned food)		45		
Cloth (Life Preserver)		65	90	Rotting of Cover
Paint Brushes		65		
Small Arms, Lubricated		65	90	Mildew and rust
Instruments (clocks, Sigma Volt Meters, Telescopes, etc.)		45		

*A - No visible deterioration
*B - Very slight deterioration
*C - Intolerable deterioration

The data in Table 3-1 indicate the necessity for a low humidity for the preservation of unprotected carbon steel but such steel as in the form of small arms, lubricated, can tolerate 65 percent like most of the other items listed. An upper humidity limit for tinned cans was not found but such cans probably can withstand at least 80 percent relative humidity.

During the tests on which the data in Table 3-1 are based only the humidity and not the temperature, was controlled. The tests were conducted in enclosures exposed to the weather and the inside temperatures closely followed the weather. This probably approximates the condition within a ship in storage which was the point of interest in this investigation. As a result of the tests and other considerations, a humidity of 35 percent was chosen for the interior of many ships placed in storage following World War II. This 35 percent is considerably below the demonstrated tolerance of many materials but it affords a factor of safety against equipment failure and against sharp temperature changes that might cause condensation on some objects due to temperature lag resulting from heat capacity.

An advantage of underground storage is steadiness of temperature. For this reason a smaller factor of safety is deemed adequate in an underground chamber and it appears that a condition of 75°F and 50 percent humidity, recommended for personnel efficiency and feasibility with conventional compressor

equipment is satisfactory for storage and use of most materials and equipment. Special low humidity may be required for instrument shops or other spaces where steel or other sensitive materials are worked without lubrication or rust preventives.

Water is essential to most kinds of material deterioration. Some metals are attacked by oxygen, atmospheric contaminants or electrolytic action in the presence of water. Organic materials support mold or mildew, when damp or moist. Obviously, therefore, condensation must be prevented on or within materials in storage. Some materials, however, are sufficiently hygroscopic to absorb damaging amounts of water at humidities less than 100 percent. Therefore some humidity safely below the saturation point must be maintained.

Pure, distilled, water is an active solvent for some materials and may be responsible for some deterioration. Atmospheric contaminants including sulfur dioxide and hydrogen sulfide, present in some industrial region atmospheres, are injurious to some materials. The amounts present during the tests on which Table 2-1 is based are not known. The tests were conducted at the Philadelphia Navy Yard.

Excessive dryness is harmful to some materials. Commutator brushes in electric motors suffer by "dusting" at low humidities. Paper, excelsior, straw, leather, hemp rope and feathers, as in bedding, become brittle and disintegrate upon handling under these conditions. Typical glue does not seriously lose strength in dry atmospheres but woods in general

shrink and the forces generated are often sufficient to break joints in furniture or other wooden equipment. Dry batteries also deteriorate more rapidly at low humidities.

The metal parts of munitions can be stored under the same condition as machine tools. For propellants, air conditions with relative humidity not exceeding 60 percent and temperature between 30 and 80°F have been recommended. In surveillance tests it has been found that powder that had lost potency had been exposed to either dampness or relatively high temperature for considerable periods. It is also regarded as good practice to avoid sub-freezing temperature and extreme dryness. Exact data on the conditions causing deterioration are lacking — and the best means of preventing or retarding deterioration is to maintain optimum conditions at all times.

Explosives may often be stored in relatively small chambers remote from each other to minimize the effects of accidents. The air conditioning equipment for such chambers should be selected with reference to minimizing pipe and duct runs. Since occupancy may be infrequent, little or no ventilation may be required. This indicates that equipment capable of dehumidifying and moderately heating such chambers is applicable in many typical cases.

2-06 Fresh Air for Personnel

The amount of fresh or outside air required actually depends on activity or rate of doing work. Present practice, however, is to supply sufficient air to avoid unpleasant odors from persons, from tobacco smoke, from cooking or other products due to occupancy. No reason appears for departing from this practice in underground installation for any normal period of operation. Selection of a fresh air requirement is complicated by the factor of intermittent occupancy which relates room volume to air change rate for equal air freshness. This situation is reflected in the data in Table 2-2, taken from reference 1.

TABLE 2-2

Minimum Outdoor Air Requirements to Remove Objectionable Body Odors Under Laboratory Conditions

Type of Occupancy	Air Space per Person, Ft^3	Air Supply CFM
Heating Season, Air not conditioned		
Sedentary Adults of Average Socio-economic Status	100	25
	200	16
	300	12
	500	7
Laborer	200	23
Sedentary Adults, Heating Season	200	12
" " Cooling Season	200	4

The available data are not conclusive. Those contained in references 1 and 2 indicate that 10 cfm per person is satisfactory for space occupied by non-smokers while 15 cfm or more is necessary to prevent objectionable odors when heavy smoking prevails. Lower rates of air supply might serve satisfactorily for underground installations during normal operation but technical data on which to base such recommendations are not available.

Fresh air must be conditioned, sometimes including cleaning, before introduction to occupied spaces. If complete protection is required against radioactive particulates, gases and biological agents it must also be purified [5-10].

2-07 Disaster Condition Air Supply

During an extreme emergency or disaster condition all outside services may be cut off and the supply of fresh air may be stopped either because of power failure or deliberately because the locality has been contaminated with radioactive material, biological agents or gases. Under this condition the occupants of an underground installation may be forced to rely on resources available in the installation for their respiration air supply. The situation will be similar in many respects to that in a submerged submarine.

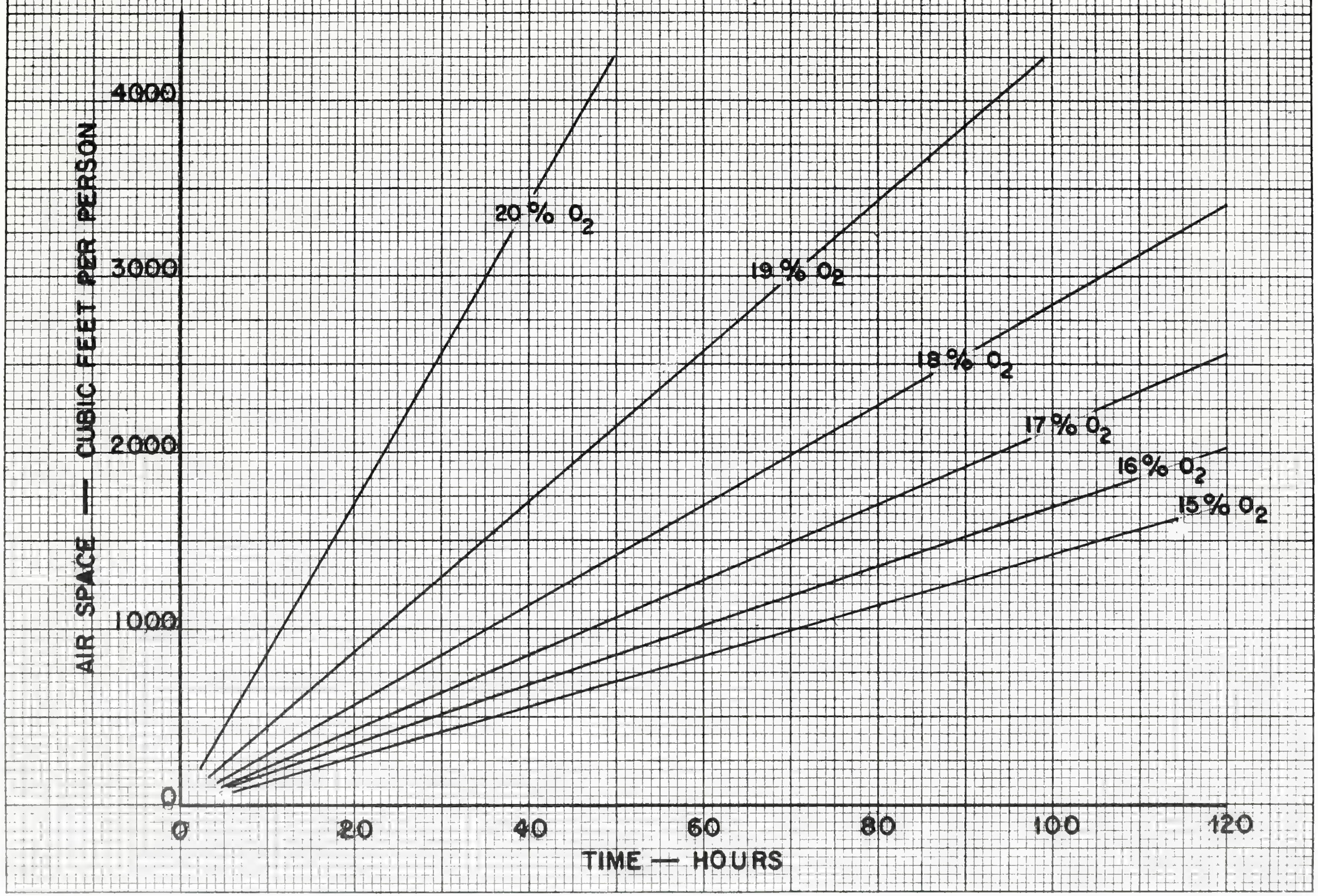
People thus isolated from a fresh air supply can subsist for some hours or days on the air in the space and the length of time depends on the volume of the air available and the number of persons present. Each sedentary person can be

expected to consume on the order of 0.05 cubic foot of oxygen and exhales about 0.7 cubic foot of carbon dioxide and liberates 0.17 pounds of water vapor per hour. When the atmospheric oxygen content is reduced from the normal 21 percent to about 14 percent or when the CO_2 content is increased from the normal fraction of a percent to more than 3 percent serious loss of vitality and ability occurs. Somewhat worse conditions result in death by suffocation. The data given on figures 2-1 and 2-2 based on sedentary occupancy show that considerable time must elapse before these danger points are approached if the volume of the space is large compared to the number of occupants but in a crowded space the limits may be reached in a comparatively short time.

Some preventive means can be provided, for use before dangerous limits are approached, based on submarine practice. Carbon dioxide can be removed from the air by means of various absorbents. In use for emergencies the sorbents are spread on rubber blankets or other suitable surface and exposed to the air. Increasing the air flow in contact with the material, as by means of fans, if available, accelerates the reaction. Oxygen can be provided under pressure in bottles or it can be generated by burning special chlorate candles. Table 2-3 shows the amount of chemicals required for air revivification under dynamic conditions.

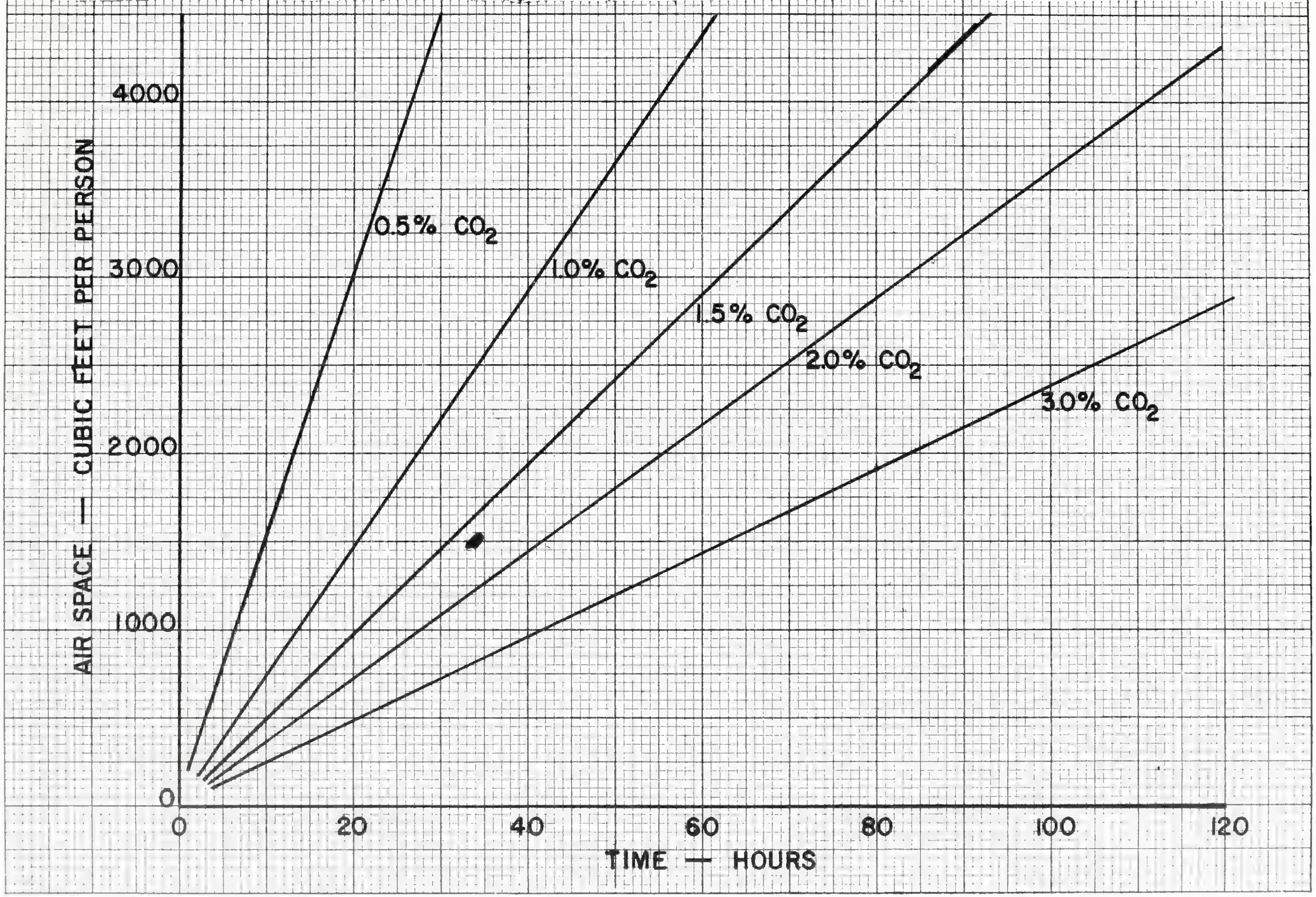
These processes also liberate heat so the relative importance of temperature rise and humidity rise should be taken into account in the design for the disaster condition. In any

FIG. 2-1 OXYGEN DEPLETION IN UNVENTILATED OCCUPIED SPACES.



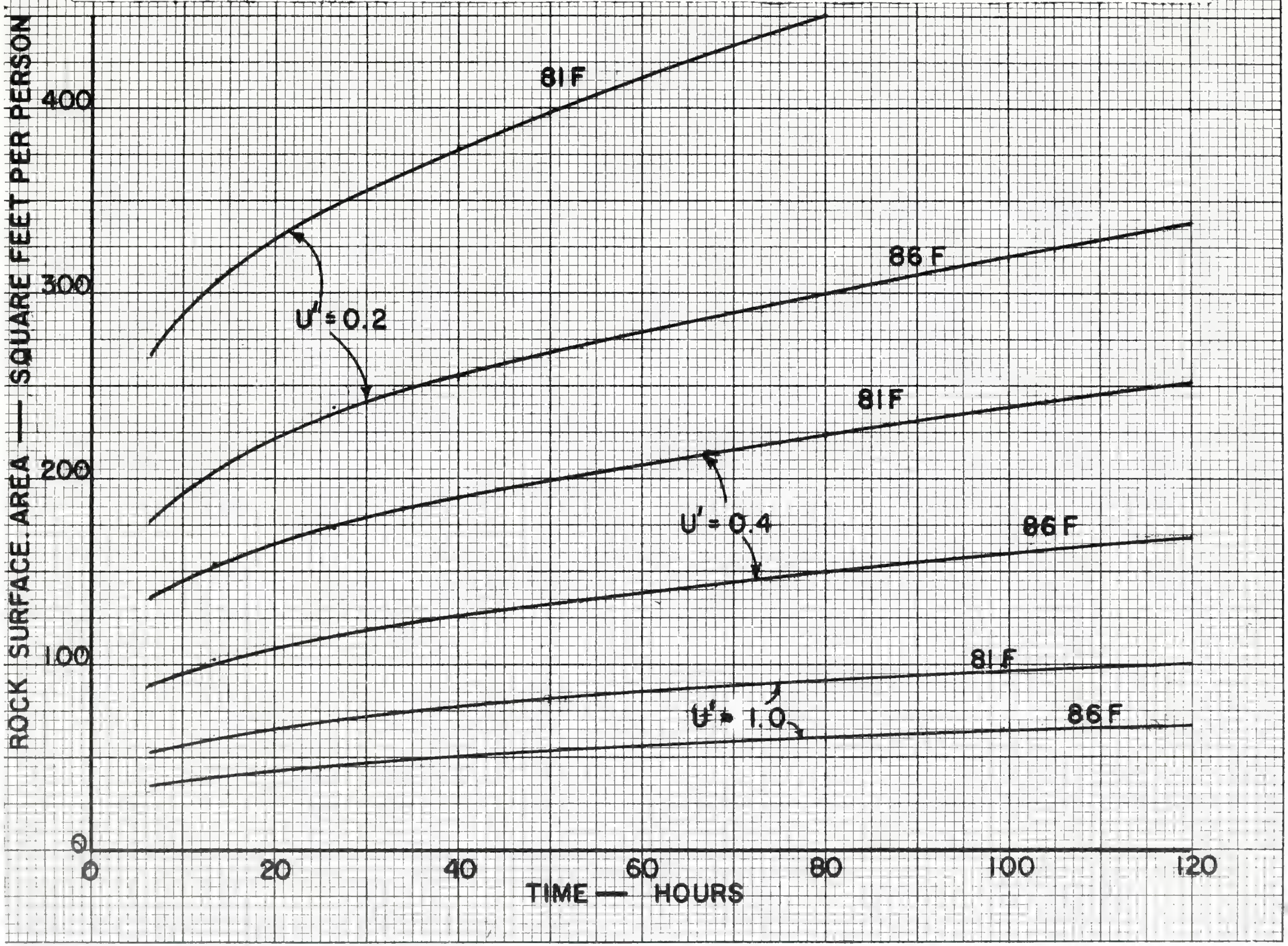
[illegible]

FIG. 2-2 CARBON DIOXIDE CONCENTRATION IN UNVENTILATED OCCUPIED SPACES.



[illegible]

FIG. 2-3 TEMPERATURE RISE IN UNVENTILATED OCCUPIED SPACES.



[illegible]

rise in RH above normal heat will flow into the rock temporarily and the dewpoint would be determined largely by rock surface temperature. Therefore, relative humidity would not approach 100 percent for some time.

Personnel in a crowded space, ventilating as above, can be expected to suffer from excessive heat and humidity. The probable period of isolation has been estimated for some purposes as one week while relief or rescue is pending. During that time the temperature is not expected to become unbearable in the absence of normal supplies of heat and power. It is estimated that personnel under disaster conditions might be exposed to temperatures of 85 or 90 F at humidities approaching 100 percent. This is not beyond human endurance but it is beyond the range at which work with paper, instruments or electronic equipment can be reliably accomplished. An enforced limitation of activity during disaster conditions would prolong the period of comfort. In extreme situations lying down on the bare rock surface would promote heat transfer from the body.

If personnel are expected to perform under a disaster condition, some means of reducing the humidity is essential.

Table D-3. Properties of Chemicals for Air Revitalization

Chemical	CO_2 Absorbed	O_2 Liberated	Weight Required lbs/man-hour	Water Vapor Formation	Sensible Heat Liberation, BTU
Lithium Hydroxide	x		0.128	yes	150 per cu.ft. CO_2
Soda-Lime	x		0.34	yes	135 per cu. ft. CO_2
Baralyme	x		0.474	yes	
Sodium Superoxide	x	x	0.[illegible]	no	174 per cu. ft. CO_2 and O_2
Potassium Tetroxide	x	x	0.364	no	147 per cu.ft. CO_2 and O_2
Chlorate Candle		x	0.24	no	64 per cu. ft. O_2

Note: These chemicals, if used, must be handled and stored with due caution. In particular sodium superoxide and potassium tetroxide are strong oxidizing agents and can be a fire hazard. This fact may preclude their use in some cases. Chlorate candles should come packaged specifically to avoid fire hazard.

Table D-3 is based on forced air flow through the chemicals (except chlorate candle) and an oxygen consumption of 1 cubic foot per man-hour and carbon dioxide liberation of 0.83 cubic foot per man-hour.

CHAPTER 3

Design Information and Data

3-01 Heating and Cooling Load Estimates (3-02 through 3-06)

Steps recommended for determining the net loads for heating and air conditioning equipment are set forth below. The purpose is to determine first, the required rate of steady heating to bring the chamber from its initial temperature to a desired air temperature (warmup period), and second, the net rate of heating or cooling required to maintain the chamber at the desired constant air temperature subsequently.

A. For the warmup period (use Form C(1-07))

(1) For each chamber, compute the constant rock heat absorption rate, q', for the desired warmup period, t_o, and final chamber temperature, T_1. Determine $\Delta q'$ for each chamber.

(2) For the whole installation, add the values of $\Delta q'$ for the several chambers.

B. For the constant air temperature or thermostated periods (use Forms B and D (1-07) dealing with each room or chamber separately).

(1) Determine the maximum internal sensible and latent heat loads. This represents the condition of normal operation at maximum capacity.

(2) Determine the internal sensible and latent loads under the stand-by condition.

(3) Determine the rate of rock heat absorption for a bare chamber, or the wall, floor and ceiling heat loss for an internal structure, at selected times.

(4) Subtract item 3 from the sensible heat load in item 1 to yield the cooling load for the room during normal operation. If item 3 exceeds the sensible heat load in item 1, heating rather than cooling is required for the room.

(5) Subtract the sensible heat load in item 2 from item 3 to obtain the heating load during the stand-by condition. If this sensible heat load exceeds item 3, cooling is indicated during the stand-by condition.

(6) Add the separate net sensible and latent loads for the several rooms for use in determining size and type of heating, cooling and dehumidifying equipment.

3-02 Heating Loads

The heating load of an underground chamber is the sum of the heat absorption of the surrounding rock ([illegible]), the heat used to evaporate water from damp exposed surfaces ([illegible]), and the heat necessary to warm ventilating air ([illegible]). Any heat liberated by machines, personnel or processes (3-06) in the space can be deducted from the heating load in any room or chamber provided such heat is well distributed.

The warming of an underground space typically falls into two periods, the warmup and the thermostated period (1.04). The heat required for warming the rock surrounding a chamber can be computed (4-02) by means of Equation 4-04. The heat absorbed

by the surrounding rock when a constant temperature is maintained in the chamber can be computed (4-04) by means of Equation 4-05.

3-03 Warmup; Bare Chamber

Installation of permanent heating equipment with sufficient capacity to supply all the heat necessary to achieve a very short warmup period is not recommended. The initial heat absorption rate of rock surrounding a warmed chamber (4-02) is comparatively very high. If a quick warmup is necessary, temporary oil burning heaters should be considered because permanent equipment large enough for the purpose will be much over size after a few months of operation. Electric heating (5-05) is practicable for a warmup period. However, the cost is comparatively high and the necessary wiring, transformer and heaters add to the cost unless they are provided for and chargeable to some other purpose. If a few months can be allowed for the warmup, it should be possible to warm the spaces with the permanent heating equipment, avoiding the necessity for temporary heaters. Fuel-burning heaters, if used, may often be supplied with combustion air and vented, as a temporary measure, through shafts or tunnels provided for other purposes.

Power equipment such as electric motors or internal combustion engines, used during excavation, contribute heat to a space and may alleviate the warmup problem.

The rock heat absorption is likely to be the greatest heat loss from the bare chamber during the warmup period. This is governed at any instant by the equation

$$q' = U' (T_i - T_s) \qquad 3\text{-}01$$

q' = heat flow, Btu per hour per square foot of rock surface exposed to the chamber

U' = heat transfer coefficient, Btu per hour, for one square foot of rock surface and for each degree difference in temperature between the air in the chamber and the rock surface

T_i = temperature of the air in the chamber, F, average

T_s = temperature of the rock surface, F, average

Equation (3-01) is often inadequate because the rock surface temperature, T_s, is unknown. The rock around a warmed space receives heat and T_s changes accordingly. This more complicated case is covered by Equation 4-04. (4-03)

3-04 Heating Load—Bare Chamber — Normal Operation

The necessary heat supply or net load at any instant is equal to the rock heat absorption minus the total internal load. The rock heat absorption decreases with time when the chamber air is held at a steady temperature. It is governed at any instant by Equation 3-01 but since, this equation does not take account of changes in T_s, Equation 4-05 is recommended for computing rock heat absorption.

When the internal load (3-06) exceeds the rock heat absorption the difference must be removed by some air conditioning means.

As far as heating load is concerned, a chamber lined with concrete can often be treated the same as an unlined chamber of the same size. The thermal properties of concrete are similar to those of rock and the thickness is relatively small. Acoustical or other insulating materials applied to walls or ceiling affect the heat transfer. Equation 3-01 is applicable to lined chambers, but the value of U' must be appropriately chosen for any wall surfacing material used (4-03).

3-05 Heating Load, Inner Structure

It should be possible in many instances to warm up an inner structure in a satisfactorily short time by means of the permanently installed heating equipment. The inner structure insulates the occupied space from the surrounding rock thereby reducing the heat required to attain and maintain the desired temperature. Heating equipment is usually installed with some excess capacity as a factor of safety and this can be utilized during the warmup period. The relation between heat input and warmup time can be computed by means of equation 4-04 (4-03).

Under the normal or steady temperature condition, the rock surrounding an inner structure warms more slowly than the rock around a bare chamber. The heat loss from the structure to the rock at any instant can be computed by means of equation 4-05, (4-03). Equation 3-01 is valid for an inner structure at any instant with a proper value of U' (4.03).

The heat loss from an inner structure at any instant can also be computed by the equation

$$q = U\ (T_i - T_a) \qquad (3-02)$$

q = heat flow, Btu per hour for one square foot

U = heat transmittance, Btu per hour for one square foot of wall, ceiling or floor and for each degree F in air temperature difference inner and outside the structure

T_i = air temperature, inside the structure, F

T_a = air temperature outside the structure in the annular space between the structure and the rock

Values of U (4-03) are not the same for underground structures as they are for exposed walls of surface buildings. For surface buildings, the value of U is ordinarily based on an assumption of a wind with a velocity of 15 miles per hour on the outside. Underground, the outside surface film coefficient and the transmittance, U, must be selected with proper reference to air velocity. In many cases the same inside and outside film coefficient, 1.65, probably is adequate.

Equation 3-02, like equation 3-01, is often insufficient because one temperature, T_a, is variable with time. The heat loss of the structure at any instant can be computed by means of equation 4-05, (4-03).

3-05 Cooling Loads

The net cooling load of an underground space is the sum of all internal loads minus the heat absorption of the surrounding rock (4-03). The internal loads include heat and moisture from personnel, waste heat from boilers, engines, electric motors, lights, cooking equipment or other apparatus

utilizing electric energy. Most of the power utilized in underground installations is likely to be supplied electrically and the heat liberated from electric equipment can be computed by the relation:

$$1 \text{ Kw} = 3412 \text{ Btu per hour}$$

Also

$$1 \text{ Horsepower} = 2546 \text{ Btu per hour} = .746 \text{ Kw}$$

However, because the efficiency is less than 100 percent, it is often assumed for estimating purposes that a consumption of one kilowatt of electric energy is necessary to produce one horsepower, at least for small motors.

For a motor driving a machine that converts the power to heat, such as a lathe, a grinding machine etc., all the energy utilized appears as heat in the surrounding space. If a motor drives a pump or blower, a fraction of the input energy is imparted to the fluid being pumped; the rate of energy or heat liberation in the space around the motor and driving gear is equal to the input power times the decimal equal to one minus the overall efficiency of the motor and driving mechanisms.

All the energy from electric lights, either incandescent or fluorescent, is converted into heat. Part of this heat may be removed by special water or air cooling means in some cases; otherwise it forms part of the cooling load.

Personnel liberate heat and water vapor and the rate depends on state of activity. Some typical data for design purposes are given in Table 3 - 1.

Table 3 - 1. Sensible, Latent and Total Metabolic Heat Loss Per Person, BTU hr^{-1}

Room	Sitting or Moving Slowly			Light Working		
Temp.	Sensible	Latent	Total	Sensible	Latent	Total
84	180	220	400	150	510	660
82	200	200	400	180	480	660
80	220	180	400	210	450	660
78	240	160	400	240	420	660
76	256	144	400	270	390	660
74	272	128	400	300	360	660
70	300	100	400	350	310	660
60	360	70	430	460	200	660
50	440	40	480	550	110	660
40				610	110	720

Cooking is responsible for both sensible and latent loads. For electric cooking, the total load is equivalent to the energy utilized, but part is latent while the remainder is sensible load. In most instances it may be possible to vent vapor from kitchens and avoid imposing the latent and some of the sensible load on the air conditioning coils.

If an apparatus is cooled by the evaporation of water into the surrounding air, the total load is not affected; part of the load becomes latent and the rest remains sensible load.

Fresh or outdoor air introduced for ventilation (2-06) must at times be cooled and dehumidified. The resultant load may be reduced by passage of the air through supply shafts or tunnels (4-05).

3-07 Dehumidification; Bare Chamber

The dehumidification load of a bare chamber includes water vapor from equipment and processes, if any, and personnel (3-06), dehumidification of fresh air (2-06), and evaporation from surrounding damp rock. Bare rock condenses water from the surrounding air whenever its surface is below the dew point, and, conversely, water evaporation from damp rock, or from pools, whenever the surface temperature exceeds the dew point (4-10). The rock therefore tends to govern the humidity in the chamber by holding the dew point at its own surface temperature. The rock cannot be relied upon indefinitely as a dehumidifying means because its surface warms with time when receiving heat from the air in the chamber (4-03).

Water in the liquid state either from leaks due to fissures in the rock or from condensation must be drained away by trenches, gutters, pipes, etc. Water in the vapor state, from personnel or processes as well as that due to evaporation from damp surfaces, must be removed by ventilation or by dehumidification effected by the air conditioning means provided.

3-08 Dehumidification; Lined Chamber

Use of vapor barriers (4-09) or of thermal insulating materials (4-08) in direct contact with rock surrounding under-

Fresh or outdoor air introduced for ventilation (2-06) must at times be cooled and dehumidified. The resultant load may be reduced by passage of the air through supply shafts or tunnels (4-05).

3-07 Dehumidification; Bare Chamber

The dehumidification load of a bare chamber includes water vapor from equipment and processes, if any, and personnel (1-04), dehumidification of fresh air (2-06), and evaporation from surrounding damp rock. Bare rock condenses water from the surrounding air whenever its surface is below the dew point, and, conversely, water evaporation from damp rock, or from pools, whenever the surface temperature exceeds the dew point (4-10). The rock therefore tends to control the humidity in the chamber by holding the dew point at its own surface temperature. The rock cannot be relied upon indefinitely as a dehumidifying means because its surface warms with time when receiving heat from the air in the chamber (4-03).

Water in the liquid state either from leaks due to fissures in the rock or from condensation must be drained away by trenches, gutters, pipes, etc. Water in the vapor state, from personnel or processes as well as that due to evaporation from damp surfaces, must be removed by ventilation or by dehumidification effected by the air conditioning means provided.

3-08 Dehumidification; Lined Chamber

Use of vapor barriers (4-07) or of thermal insulating materials (4-08) in direct contact with rock [illegible]

ground spaces is not generally to be recommended. The hydrostatic pressures that can be generated due to the depth of an underground working are greater than can be restrained by ordinary vapor barrier materials or even by moderately heavy concrete liners. Assuming that water head is at times as deep as the overburden, the possible pressure is represented by the equation:

$$P_W = 0.43\ d \qquad (3\text{-}03)$$

P_W = hydrostatic pressure, p.s.i.

d = depth, ft

Insulating material applied directly to rock walls or to concrete in contact with such walls is likely to be wet either by condensation or by ground water or both, with resulting damage to the insulating material or to its fastenings. A vapor barrier inside the insulation does not protect it from ground water and such a barrier outside the material does not protect it from condensation.

From these considerations it appears that, if insulation is to be used, an air space is desirable between the insulation and the rock and, if the air space is provided, there are some advantages to making its width suffifient to permit access for purposes of inspection and repair, particularly for multi-story installation. This done, the liner becomes substantially an inner structure and can be treated as such.

[illegible] is not generally to be recommended. The hydrostatic pressure [illegible] due to the depth of an underground opening, are greater than can be resisted by ordinary vapor barrier materials or even by [illegible] liners. Assuming that water head is at [illegible] as deep as the underground, the hydrostatic pressure is represented by the equation:

$$P_w = 0.43\,h$$

where P_w = hydrostatic pressure, p.s.i.

h = depth, ft.

Insulating material applied directly to rock walls or to concrete in contact with such walls is likely to be wet either by condensation or by ground water or both, with resulting damage to the insulating material or to its fastenings. A vapor barrier inside the insulation does not protect it from ground water and such a barrier outside the material does not protect it from condensation.

From these considerations it appears that, if insulation is to be used, an air space is desirable between the insulation and the rock and, if the air space is provided, there are some advantages in making its width sufficient to permit access for purposes of inspection and repair, particularly for multi-story installation. This done, the liner becomes substantially an inner structure and can be treated as such.

A concrete liner may be installed in an underground space to improve its appearance or to reduce the changes of spalling but it should not be considered effective as either thermal insulation or a vapor barrier. The dehumidification load in such a space is subject to the same considerations as those for a bare chamber.

3-09 Dehumidification; Inner Structure

If the walls, ceiling, and floor of an inner structure are vapor proof, the water vapor to be removed by the air conditioning apparatus is equal to that liberated by the equipment and personnel (3-06) within the structure. Conditions in the annular space do not directly affect those within the structure.

If the walls, ceiling, and floor of the inner structure are pervious, the water vapor to be removed by the air-conditioning apparatus is then the algebraic sum of the water vapor liberated by personnel and equipment and that entering the inner structure through the walls, ceiling, and floor by permeation, or by convection from the annular space.

Compared to convection, migration of water vapor by either capillarity or diffusion through a material may have feeble and often negligible effects in transferring water vapor. Leaks exist in most ordinary structures and therefore if a difference in air pressure is maintained between the inside and outside of an inner structure, the interior humidity is likely to be governed by the resultant air flow.

In the absence of an air pressure difference, migration of vapor through a barrier such as a wall or ceiling may be estimated on the assumption that the flow is proportional to the vapor pressure difference and to the permeance of the barrier (4-09).

The surrounding rock can be relied upon as a dehumidifying (and cooling) means so long as its surface remains cool. If the surface becomes warm, due to heat received from the inner structure or due to the passage of warmer air through the annular space, the rock will cease to be a means for maintaining a satisfactorily low humidity.

3-10 Waste Heat Disposal

During normal operation waste heat from such equipment as Diesel engines, refrigeration condensers, etc., can be dissipated in water as from a brook, river, or creek if available or into the air by means of air cooled or evaporative condensers or cooling towers. However, during attack or under some post attack conditions (1-05) it may sometimes be necessary to utilize heat disposal means built into or in conjunction with the underground installation.

An underground reservoir is an obvious and practical heat sink for use when outside water service is cut off. It must be adequate in size or capacity to absorb the waste heat from the equipment to be operated for the duration of the estimated period of isolation.

There are two ways to utilize an underground reservoir (4-04). The water can be passed through the equipment to be cooled and wasted outside the installation, or the water can beused to absorb heat while remaining in the reservoir. Somewhat more heat can be absorbed by a reservoir of a given size when the heat is added to the water while it remains in the reservoir because the surrounding rock also absorbs heat. A possible disadvantage of the method for a reservoir of limited size, is that the surrounding rock will be left warm at the end of a period of isolation and may require too much time and water for cooling in preparation for the next attack. If a reservoir is large compared to the load imposed upon it, the arrangement can serve for a long period of time.

For estimating purposes it can be assumed that, for an internal combustion engine, about 30 percent of the heat value of the fuel burned appears in the jacket cooling water. For an air conditioning refrigerating machine, the condenser and jacket cooling water receive about five times the heat equivalent of the electric energy that drives the compressor.

The heat absorbing capacity of a reservoir with wastage of water outside after use is given by equation 4-07. The heat absorbing capacity of an underground reservoir as a function of time, if the water is recirculated and retained, is given by equation 4-08.

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The heat absorbing capacity of a reservoir with wastage of water outside after use is given by equation 1-07. The heat absorbing capacity of an underground reservoir as a function of time, if the water is recirculated and retained, is given by equation 1-08.

3-11 Air Conditioning Effect of Tunnels or Shafts

The initial or undisturbed temperature in a tunnel or shaft with an overburden of 50 feet or more is likely to be at or near the mean annual temperature which is in the range 50 to 55 F in many regions. This is usually above the winter outside design temperature and below the summer outside design temperature and dew point for such regions. A tunnel or shaft is therefore a possible means for tempering the air in winter or of partially conditioning it in summer. For a long tunnel and a small flow, the air passed through a tunnel assumes nearly the earth temperature, say 55 F. Also, such a tunnel can dehumidify outdoor air in summer, and humidify it in winter if ground water is present. A large wet tunnel with a small air flow can therefore condition air to approximately 55 F saturated at all seasons. Air at this condition, warmed to 75 F, assumes a relative humidity of 50 percent.

A tunnel in continuous use for transporting outdoor air extracts heat from the air in summer and imparts an approximately equal amount of heat to the air in winter. The outdoor temperature, plotted against time throughout a year describes an approximate cosine curve and the air leaving the tunnel describes a similar curve but with a smaller amplitude. The amplitude of the air temperature variation at the exit end of the tunnel indicates the heating and cooling effects of the tunnel. For a long tunnel and small air flow this

amplitude will be small, as discussed above. For any specific tunnel there is a limit to the cooling and heating capacity, depending on the dimensions, the nature of the surrounding rock, etc. The mathematical relations governing heating and cooling of outside air by tunnels are given by equation 4-10, (4-05). Remarks about tunnels in this section apply substantially also to shafts or other openings of equal dimensions.

3-12 Evaporation from Pools or Damp Surfaces

Ground water can have several effects that influence structure and equipment design, including the following. It can exert pressure on any vapor barrier or liner installed to prevent its ingress into underground spaces as shown by equation 3-03. It can affect the conductivity and heat capacity of porous or hygroscopic rock (4-08). To evaporate water from damp surfaces or open pools requires heat (4-10) and can add to the heating load. Water evaporating absorbs the same latent heat as it gives up when it condenses. Therefore in some cases the effect of evaporation as from damp surfaces in a space being cooled is not to change the total air conditioning load but is to convert part of the load from the sensible to the latent type. If a machine or apparatus is cooled by the evaporation of water and if the resulting vapor is vented outside without reaching the cooling coils, the heat conveyed is not added to the cooling load.

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3-12 Evaporation from Pools or Damp Surfaces

Ground water can have several effects that influence structure and equipment design, including the following. It can exert pressure on the walls ceiling or floor installed to prevent its ingress into underground spaces as given by equation 3-03. It can affect the conductivity and heat capacity of porous or hygroscopic rock (4-06). To evaporate water from damp surfaces or open pools requires heat (4-10) and this adds to the heating load. Water evaporation absorbs the same latent heat as it gives up when it is condensed. Therefore in most cases the effect of evaporation on free damp surfaces in a space being cooled is not to change the total air conditioning load but is to convert part of the load from the sensible to the latent type. If a machine or apparatus is cooled by the evaporation of water and if the resulting vapor is vented outside without reaching the cooling coils, the heat conveyed is not added to the cooling load.

Chapter 4

HEAT ABSORPTION OF ROCK AROUND UNDERGROUND SPACES

4-01 Principles

The geological formation around an underground installation is termed rock in this chapter. Usually, at required depths, locations will be chosen where the space will be surrounded by rock, rather than clay, sand or another material, in consideration of strength and stability requirements.

The temperature in an occupied underground space is usually maintained above that of the surrounding rock and consequently heat flows from the space to the rock. In the absence of internal load, the heat supplied to the space must equal that absorbed by the rock. When the internal load, such as the heat from lights, motors or other equipment and personnel, exceeds the heat absorbed by the rock, the difference must be removed by some cooling means such as an air conditioning apparatus.

The rock surrounding a continuously warmed space itself becomes warm with time, its surface temperature increases and its heat absorption rate decreases. Consideration of these effects is obviously essential in the computation of heating or air conditioning loads but unfortunately heat flow of this transient type is not subject to simple analysis. The pertinent differential equations

are too complex for every-day use and for this reason an approximate method has been evolved and checked against experimental results obtained in several underground spaces.

The recommended method for estimating heat absorption by surrounding rock is based on consideration of an assumed underground space, either spherical or cylindrical in shape, with thermal characteristics similar to those of a chamber to be utilized. The heat flow equations pertaining to spheres or cylinders are simpler than those for other shapes. The data presented for use with the equestions in this manual (4-03) are based on numerical solutions of the equations for cylinders and spheres obtained by means of a large electronic computer, available at the National Bureau of Standards.

Usually, a new underground space must be warmed to some acceptable temperature in preparation for occupancy. Heat may be supplied to the space for this purpose at a relatively large, constant rate. If the desired temperature and permissible warm-up time are specified, the required heat supply rate can be computed by means of Item 6 under procedure (4-02).

After the warm-up, presumably a constant temperature will be desired in the space, at or near 75°. The heating or air conditioning system is then expected to operate on thermostat. The surrounding rock absorbs heat at a rate

are the simplest for every-day use and for this reason an approximate method has been evolved and checked against experimental results obtained in several underground spaces.

The recommended method for estimating heat absorption by surrounding rock is based on consideration of an assumed underground space, either spherical or cylindrical in shape, with thermal characteristics similar to those of a chamber to be utilized. The heat flow equations pertaining to spheres or cylinders are simpler than those for other shapes. The data presented for use with the equations in this manual (4-03) are based on numerical solutions of the equations for cylinders and spheres obtained by means of a large electronic computer, available at the National Bureau of Standards.

Usually, a new underground space must be raised to some acceptable temperature in preparation for occupancy. Heat may be supplied to the space for this purpose at a relatively large, constant rate. If the desired temperature and permissible warm-up time are specified, the required heat supply rate can be computed by means of Item 4 under procedure (4-02).

After the warm-up, presumably a constant temperature will be desired in the space, at or near 70°F. The heating or air conditioning system is then intended to operate on thermostat. The surrounding rock absorbs heat at a rate

that decreases with time and the absorption rate at any instant can be computed by means of Items 7 and 8 under procedure (4-02).

4-02 Procedure for Estimating Heat Transfer, Air to Rock

The procedure recommended for estimating heat transfer from an underground space to surrounding rock is as follows:

1. Compute the internal surface area of the space. Projected areas can be used; irregularities left in walls, ceilings, and floors after blasting can be ignored. Equation 4-01 is applicable.

2. Obtain the value of V_1/V for the cylinder by means of Figure 4-1 and of V_2/V for the sphere by means of Figure 4-2.

3. If V_1/V exceeds V_2/V, utilize the cylinder as the best approximation to the space considered; if V_2/V exceeds V_1/V, utilize the sphere.

4. Compute the radius of a cylinder of the same internal area using Equation 4-02 and compute the radius of a sphere of the same internal area by means of Equation 4-03.

5. Determine the initial temperature of the rock, thermal conductivity, density, specific heat, and overall coefficient of heat transfer. These may be found from

geologic data, testing of samples, or estimated from information given in section 4-06, 4-07, and 4-08.

6. For a given warm-up time (4-03), determine the required heat input by means of Equation 4-04. Utilize Figure 4-3 for the cylindrical case or 4-4 for the spherical case in conjunction with this equation. Data Form C is suggested as a work sheet (1-07).

7. Compute the rock heat absorption for the constant air temperature, or thermostated condition (4-03), by means of Equation 4-05. Equation 4-05 will yield the heat absorption for the cylinder or for the sphere, whichever was selected for an approximation to the space being considered.

8. Adjust the results obtained under Item 7; divide the heat absorption obtained for the cylinder by the ratio V_1/V or divide the results obtained for the sphere by the ratio V_2/V. This will yield an approximation to the heat absorption for the space under consideration that can be used in heating and air conditioning load estimates. Data Form D is suggested as a work sheet (1-07).

4-03 Equations for Heat Transfer, Air to Rock

Equations applicable to the procedure for computing heat absorption by rock are as follows:

Area of an Underground Chamber, either square or rectangular.

$$A = 2\,(mn + ms + ns) \qquad (4\text{-}01)$$

A = wall, ceiling and floor area, ft^2

m = length, ft

n = width, ft

s = ceiling height, ft

If the space is not a parallelepiped, that is if the ceiling is arched or if either major irregularities in shape exist, the area, A, should be adjusted accordingly by some appropriate method.

Radius of a cylinder with thermal characteristics approximately similar to those of the space considered:

$$a_1 = \frac{A}{2\pi m} \qquad (4\text{-}02)$$

Radius of a sphere with thermal characteristics approximately similar to those of the space considered:

$$a_2 = \sqrt{\frac{A}{4\pi}} \qquad (4\text{-}03)$$

Rock heat absorption; steady heat input required to warm the rock surrounding a space in a specified time:

$$\frac{\theta_s K}{q'a} = f\,(F) \qquad (4\text{-}04)$$

θ_s = Temperature rise of rock surface, above initial temperature, deg. F

K = Thermal conductivity of rock, Btu $hr^{-1}ft^{-1}$

q'= Rock heat absorption rate, Btu $hr^{-1}ft^{-2}$

a = Radius, ft; a_1, for the cylinder; a_2 for the sphere; selected for the approximation from Equation 4-02 or 4-03

F = $Kt/\rho ca^2$; F_1, cylinder; F_2, sphere

t = Time permitted for warm-up period, hrs

p = Density of rock surrounding the space, lb ft^{-3}

c = Specific heat of the rock, Btu lb $^{-1}F^{-1}$

To utilize Equation 4-04 first compute the value of F, then determine the value of $\theta_a K/q'a$ from Figure 4-03 for the cylinder or Figure 4-4 for the sphere. From the value of $\theta_a K/q'a$ thus estimated, determine the heat absorption of the rock q', in Btu per hour and per square foot. It will be noted that the heat absorption rate, determined with Equation 4-04 depends on rock surface temperature rise, θ_s.

Rock Heat Absorption; Constant Air Temperature (Thermostated Condition)

$$q = (1-\theta_s/\theta_1)\ U'\theta_1/R \qquad (4\text{-}05)$$

q = Rock heat absorption rate, Btu hr $^{-1}$ft^{-2}. The value of θ_s/θ_i in Equation 4-05 is given by Equation 4-06, and is a function of F which involves the time, t, for which the thermostated condition has been continued. It will be seen that the rock heat absorption rate q decreases as time t increases. See Form D (1-07).

U' = Overall average coefficient of heat transfer, Btu hr^{-1}ft^{-2}, for each degree temperature difference between the rock surface temperature and the temperature of the air within the heated or air conditioned space. For an internal structure, the relevant air temperature is that inside the structure. (4-08)

θ_i = Temperature difference, air temperature to be maintained in the air conditioned space minus initial rock temperature, deg F.

θ_s = Temperature rise of rock surface, above initial rock temperature, deg. F.

x = V_1/V for the cylinder or V_2/V for the sphere. Values are taken from the charts, Figures 4-1 and 4-2. These values are

used also for choosing between the cylindrical and spherical approximate solutions as stated in item 3 under procedure

$$\frac{\theta_s}{\theta_i} = f\,(F,\ N) \qquad (4\text{-}06)$$

Values of θ_s/θ_i are taken from the charts, Figure 4-5 for the cylinder or Figure 4-6 for the sphere. On this figure

$$N = aU'/K$$

The quantity N must be computed for use with the charts.

For an internal structure under the thermostated condition, the heat loss per square foot from any particular room at any time equals $U_o(T_i - T_a)$, which can be shown to equal

$$qU_o\left[\frac{R}{U'} + 0.7\right]$$

where q is given by Equation 4-05, U_o is taken from Table 4.1 (4-08) for the internal structure, and R and U' are as defined for Equation 4-05. The total heat loss from the room is the sum of the losses from the walls, ceiling, and floor.

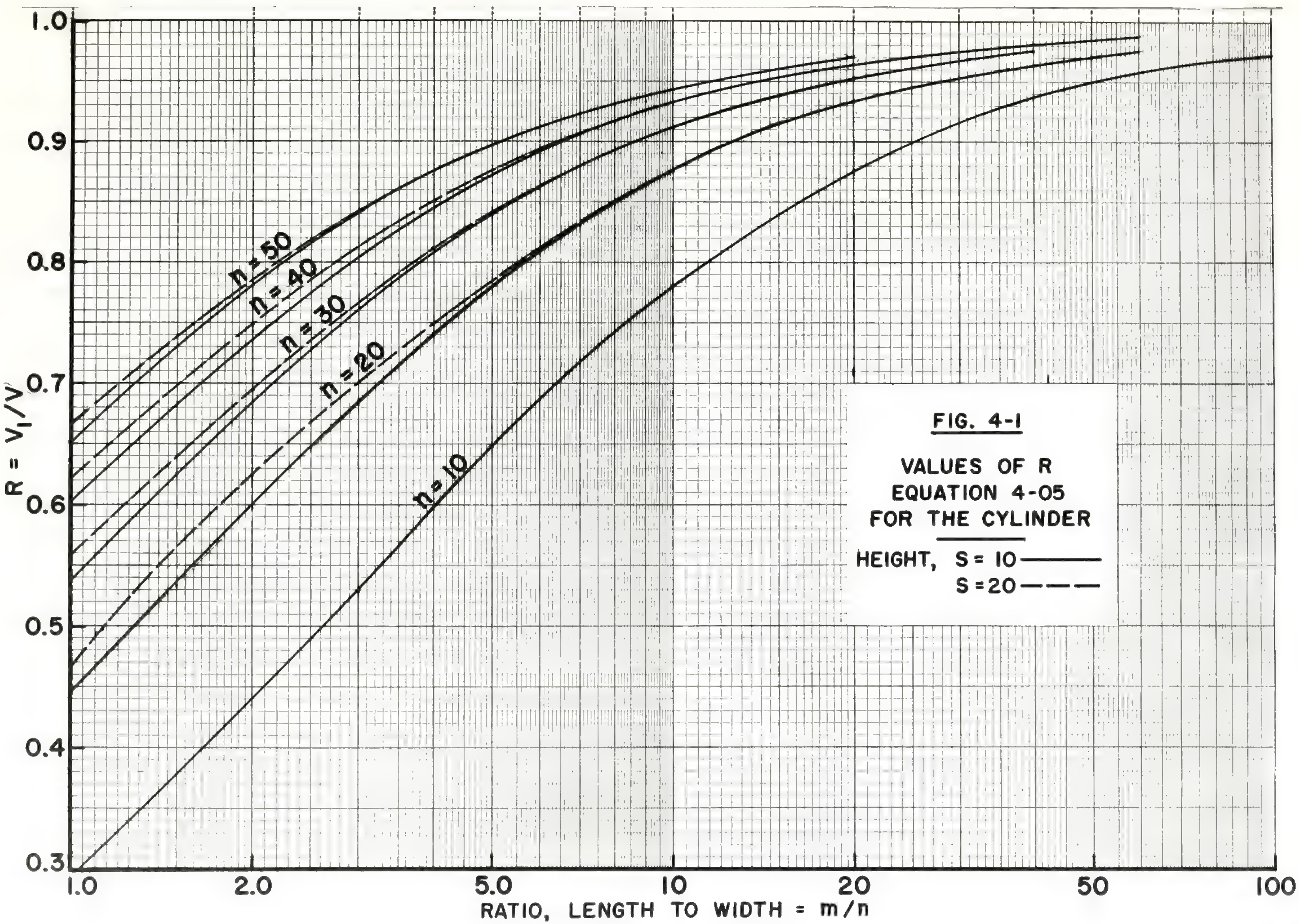

FIG. 4-1

VALUES OF R
EQUATION 4-05
FOR THE CYLINDER

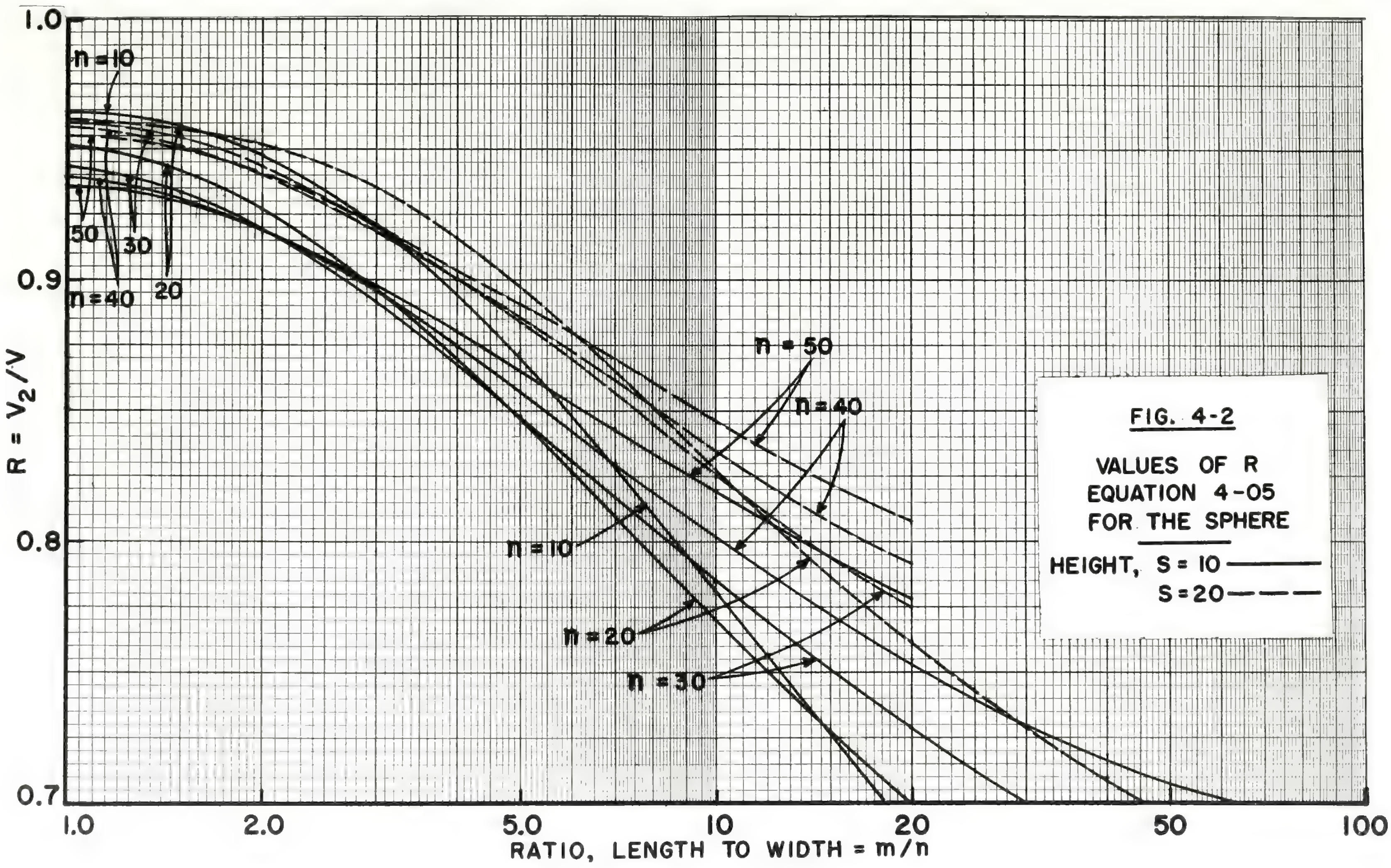

FIG. 4-2
VALUES OF R
EQUATION 4-05
FOR THE SPHERE
HEIGHT, S = 10
S = 20
R = V2/V
1.0
0.9
0.8
0.7
1.0
2.0
5.0
10
20
50
100
RATIO, LENGTH TO WIDTH = m/n
n = 10
n = 20
n = 30
n = 40
n = 50
50
30
20

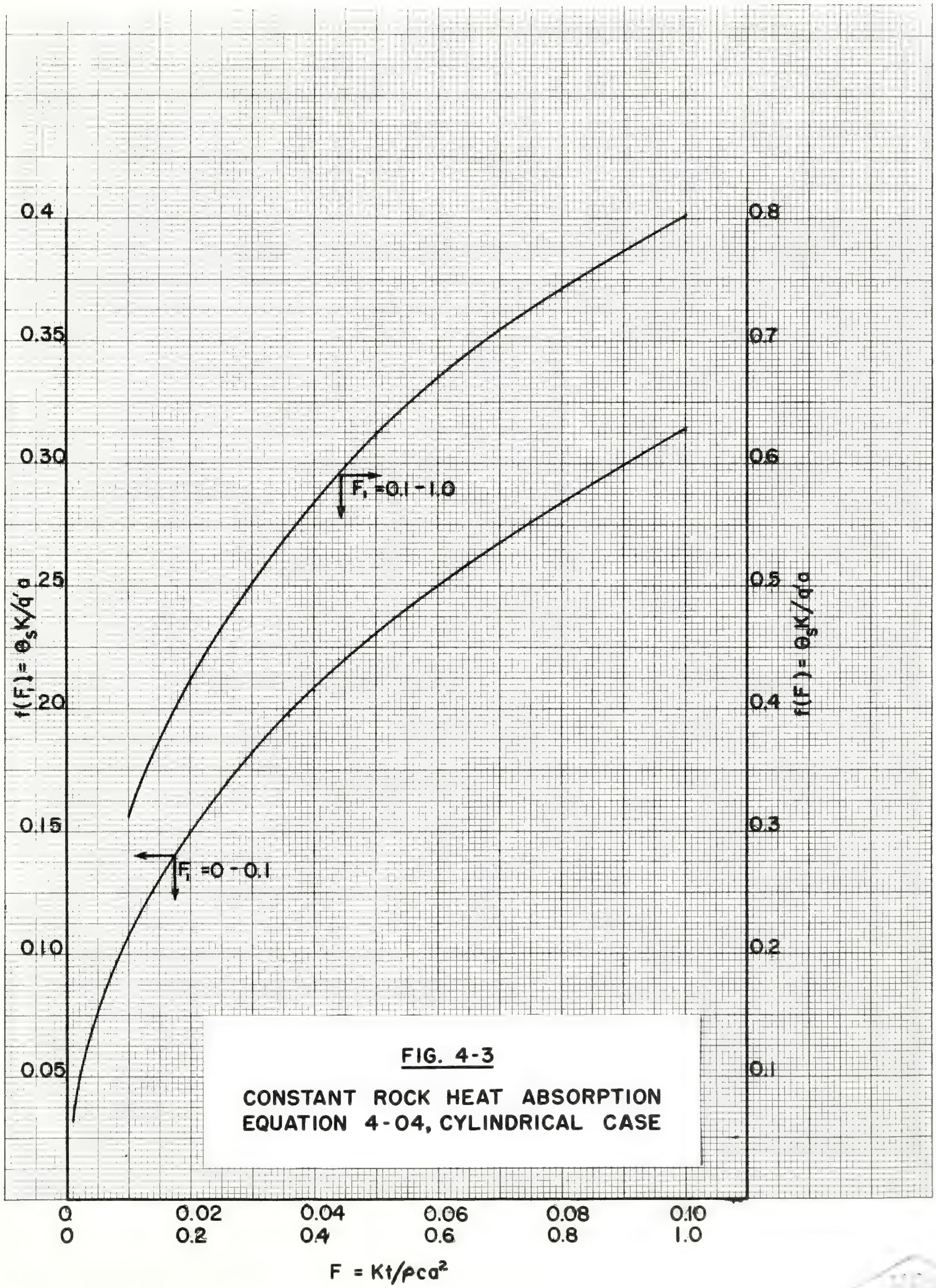

FIG. 4-3

CONSTANT ROCK HEAT ABSORPTION
EQUATION 4-04, CYLINDRICAL CASE

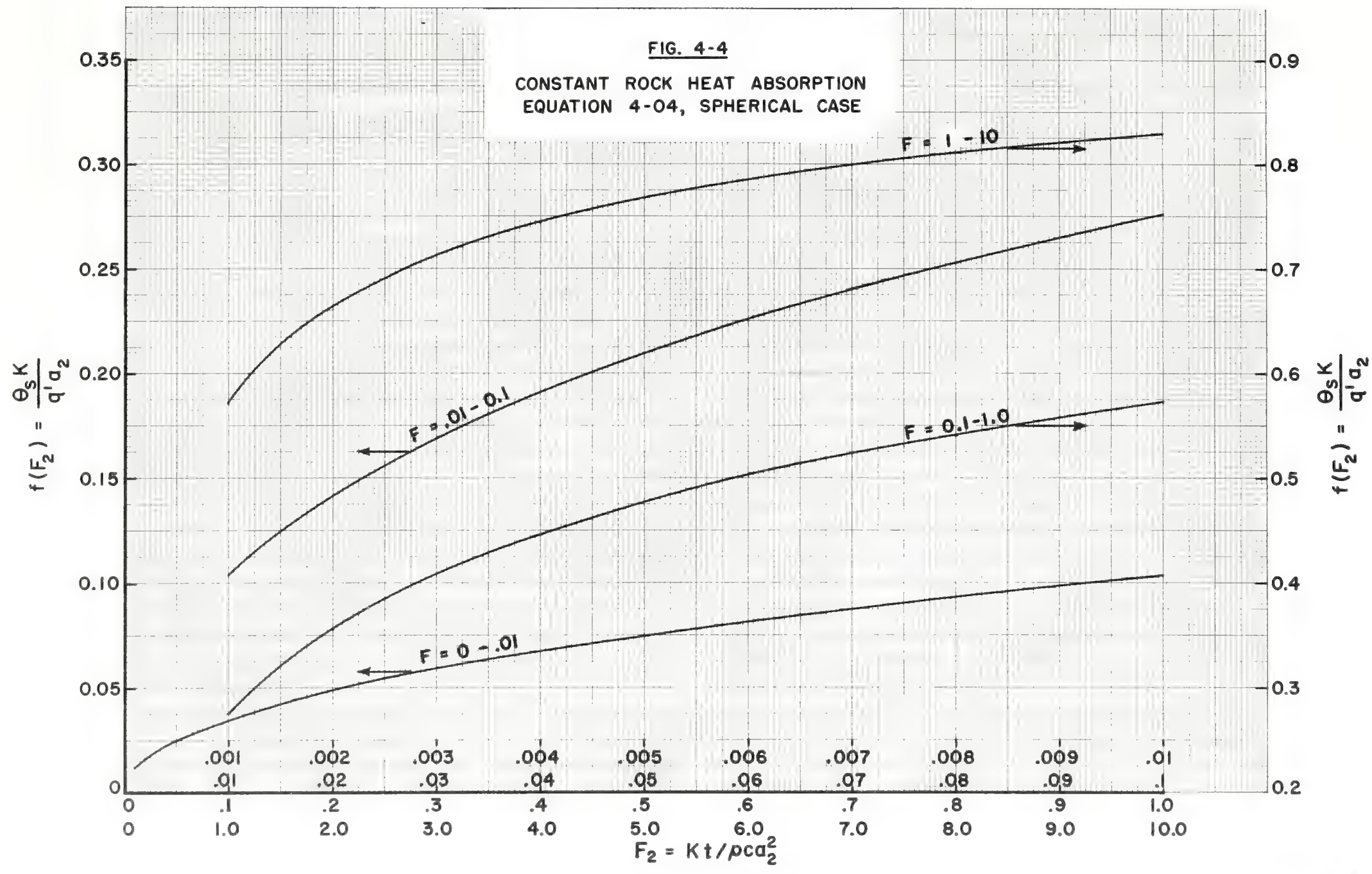

FIG. 4-4
CONSTANT ROCK HEAT ABSORPTION
EQUATION 4-04, SPHERICAL CASE
F = 1 - 10
F = .01 - 0.1
F = 0.1-1.0
F = 0 - .01
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
$f(F_2) = \frac{\theta_s K}{q' a_2}$
$f(F_2) = \frac{\theta_s K}{q' a_2}$
.001 .002 .003 .004 .005 .006 .007 .008 .009 .01
.01 .02 .03 .04 .05 .06 .07 .08 .09 .1
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0
$F_2 = Kt/\rho c a_2^2$

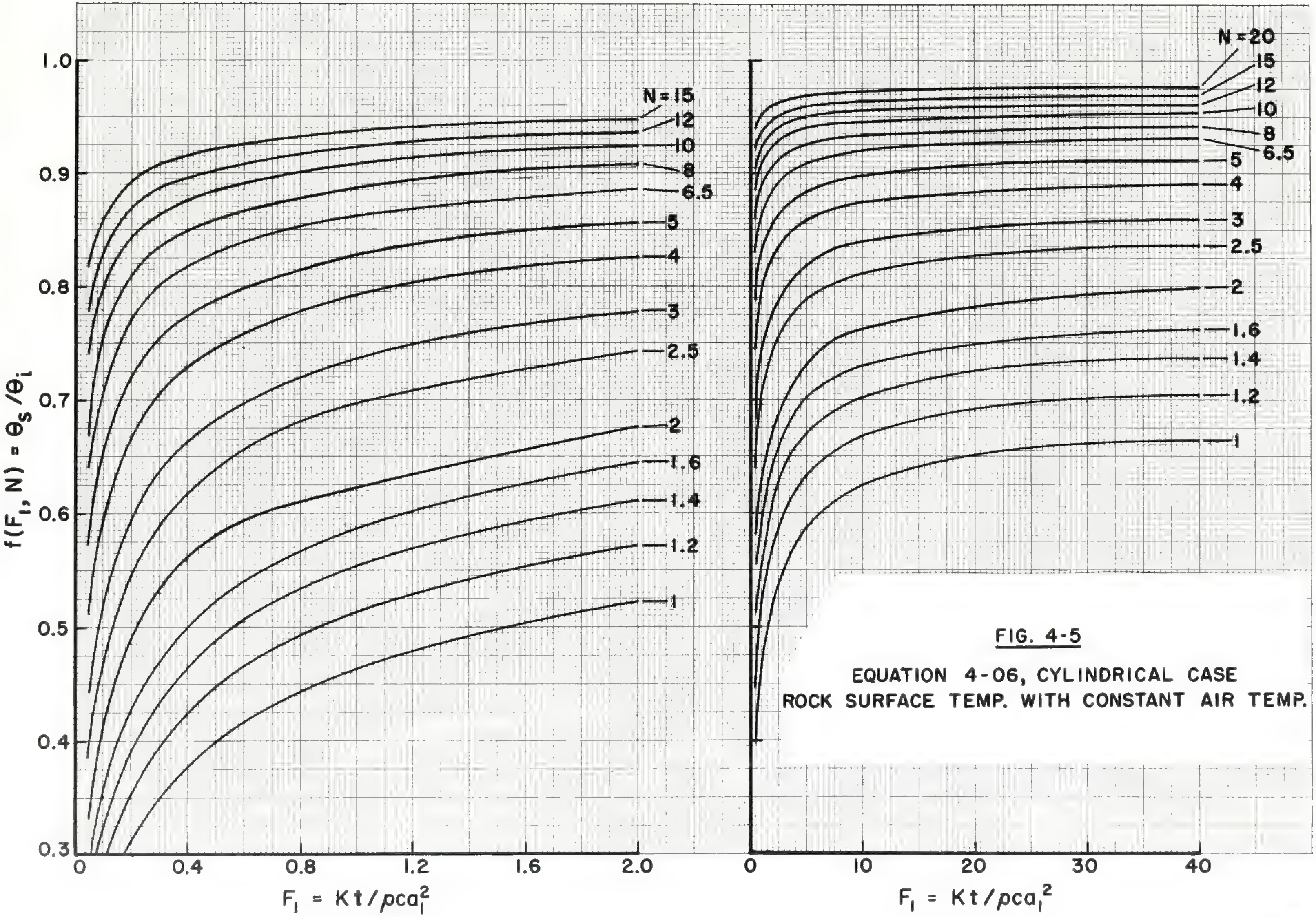

FIG. 4-5

EQUATION 4-06, CYLINDRICAL CASE
ROCK SURFACE TEMP. WITH CONSTANT AIR TEMP.

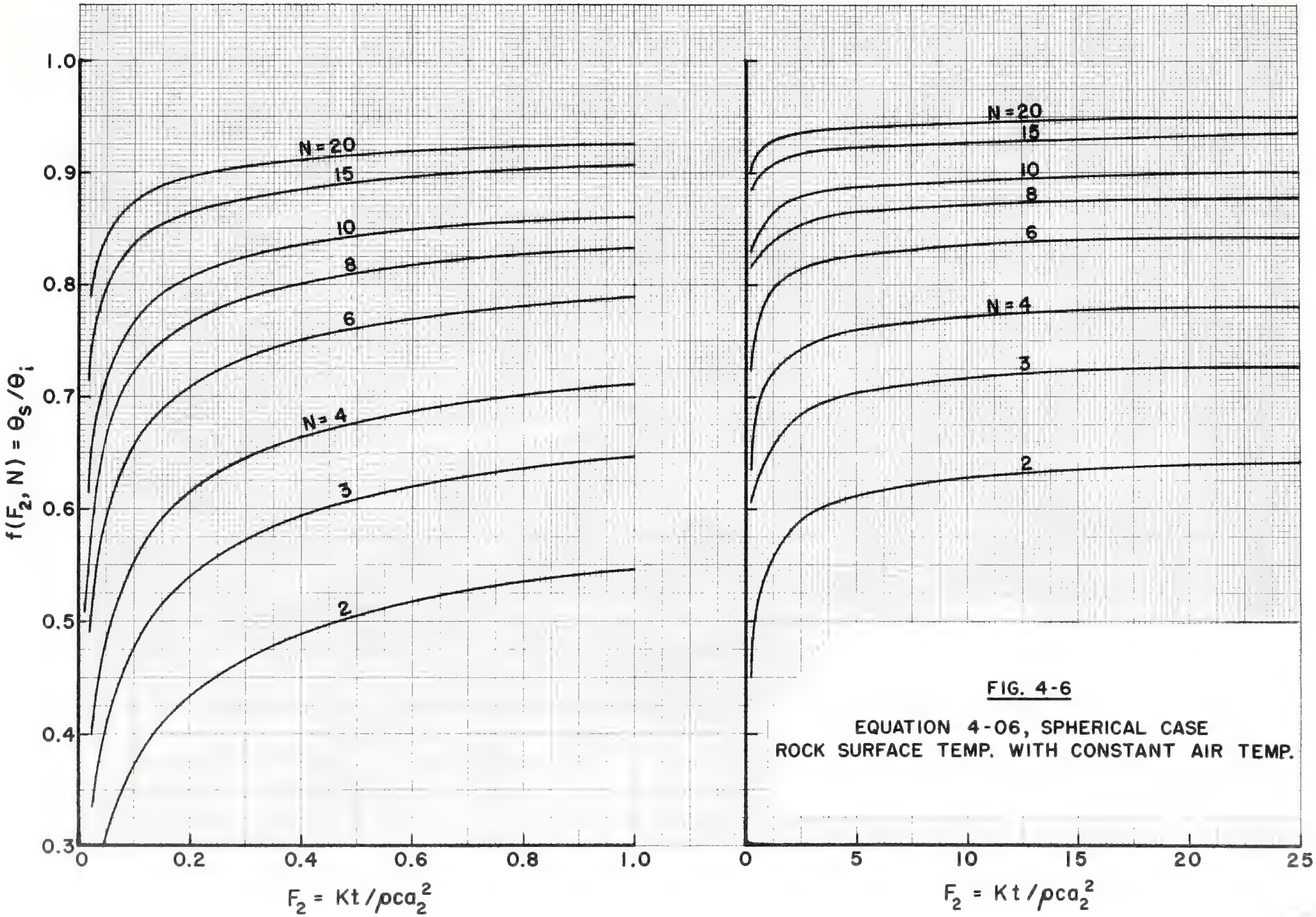

FIG. 4-6

EQUATION 4-06, SPHERICAL CASE
ROCK SURFACE TEMP. WITH CONSTANT AIR TEMP.

4-04 <u>Heat Absorption of Underground Reservoirs</u>

An underground reservoir of water may be provided as a sink for the waste heat from engines, air conditioning equipment or other apparatus for use during emergencies (1-5) when outside services are cut off (3-10). Spaces prepared for this purpose are likely to be long and tunnel-like for reasons of economy in excavation and to provide necessary rock surface area. Therefore, in the capacity calculations the tunnel shape is assumed and the cylindrical approximation is employed.

If the water is used to absorb heat from engine jackets or refrigeration condensers, etc., and is then wasted outside the installation, its heat absorbing capacity can be computed by the equation:

$$Q_W = M\ (T_W - T_p) \qquad (4\text{-}07)$$

Q_W = Heat absorbing capacity of the water, Btu

M = Mass of water in the reservoir, lbs

T_W = Temperature; water discharged from engine jacket or condenser, etc. F

T_p = Temperature; water available from reservoir, F

If the water is recirculated from the reservoir to the engine jackets or condenser and back to the reservoir the heat-absorbing capacity is increased by the heat-absorbing capacity of the surrounding rock and the total capacity can be computed by means of the equation:

4-04 Heat absorption of Underground Reservoirs

An underground reservoir of water may be provided as a sink for the waste heat from engines, air conditioning equipment or other apparatus for use during emergencies (4-5) when outside services are cut off (3-16). Rooms prepared for this purpose are likely to be long and tunnel-like for reasons of economy in excavation and to provide necessary rock surface area. Therefore, in the capacity calculations the tunnel shape is assumed and the cylindrical approximation is employed.

If the water is used to absorb heat from engine jackets or refrigeration condensers, etc., and is then wasted outside the installation, its heat absorbing capacity can be computed by the equation:

$$Q_w = M (T_w - T_p) \qquad (4-07)$$

Q_w = Heat absorbing capacity of the water, Btu

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T_p = Temperature; water available from reservoir, F

If the water is recirculated from the reservoir to the engine jackets or condenser and back to the reservoir the heat-absorbing capacity is increased by the heat-absorbing capacity of the surrounding rock and the total capacity can be computed by means of the equation:

$$\frac{\theta_w K}{q_1} = f\ (F,\ G) \qquad (4\text{-}08)$$

where

θ_w = Temperature rise of water above the initial water temperature, deg F

q_1 = Constant heat transfer rate to the water from an external source such as engine jackets or condenser, Btu hr^{-1} per foot length of reservoir

F = $Kt/\rho c a^2$

t = Time from initial application of q_1, hours

a = $(s+n)/\pi$, radius of equivalent cylinder, ft

s = Height of reservoir, ft

n = Width of reservoir, ft

G = $\dfrac{2\pi a^2 \rho c}{M'c'}$

= $2\rho c/\rho' c'$ (for a cylinder completely filled with water)

M' = Mass of water in reservoir, lbs per foot length of reservoir

ρ' = Density of water, lbs ft^{-3}

c = Specific heat of rock, Btu $lb^{-1}F^{-1}$

c' = Specific heat of water, Btu $lb^{-1}F^{-1}$

m = Length of reservoir, ft

Equation 4-08 is plotted in Figure 4-7 and Form 1 is suggested as a work sheet for its use. This equation yields the heat absorption per foot of length, q_1, for a tunnel of radius, a, for a specified water temperature rise θ_w in a specified time, t.

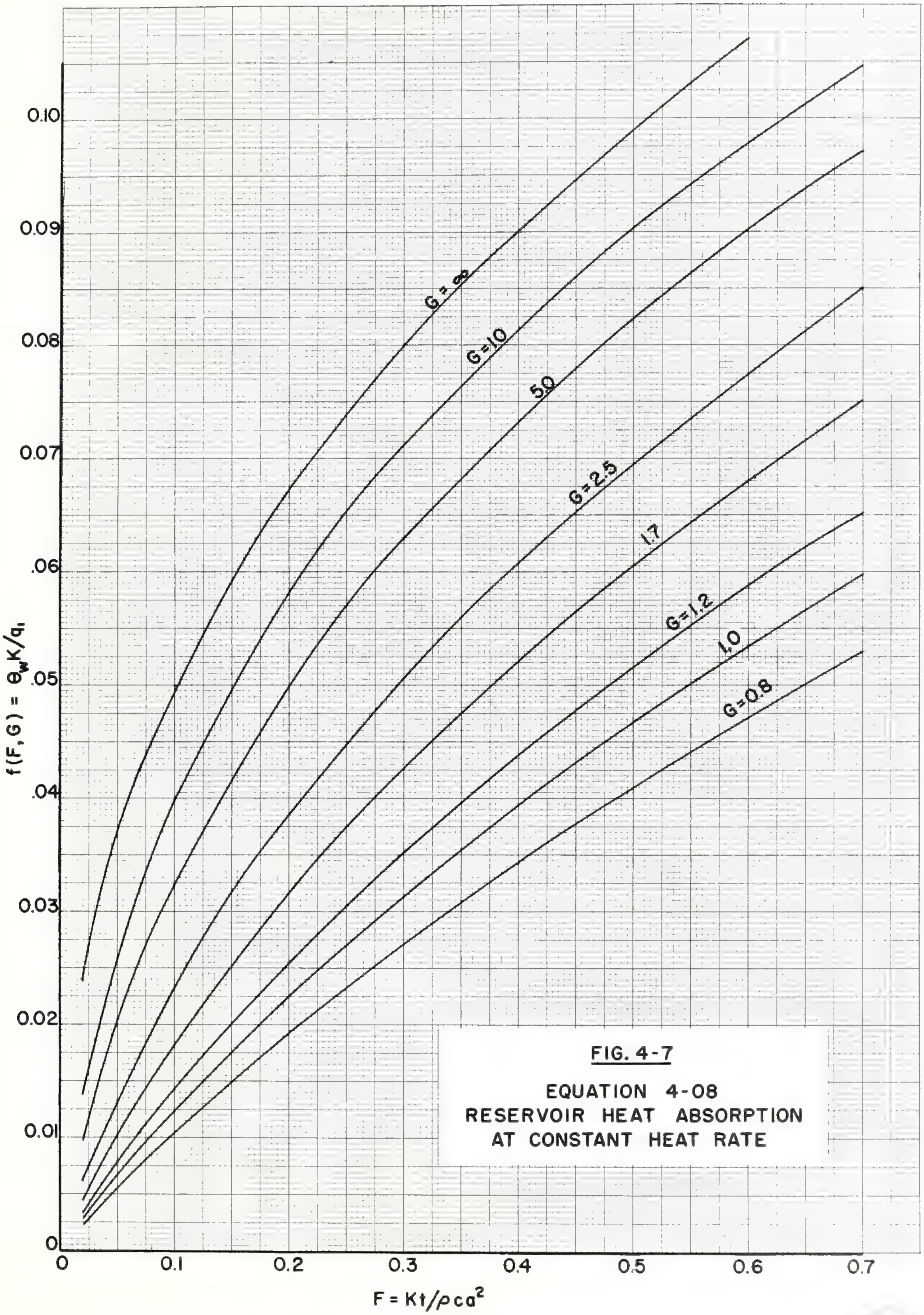

FIG. 4-7

EQUATION 4-08
RESERVOIR HEAT ABSORPTION
AT CONSTANT HEAT RATE

4-05 Heating or Cooling of Air by Tunnels or Shafts

Fresh or outside air needed for ventilation is often introduced to installations through shafts or tunnels with bare walls so that the air flows in contact with the surrounding rock. For a tunnel in continuous use, heat is alternately transferred from the air to the rock in summer and from the rock to the air in winter. Savings are possible under both conditions since the air is warmed in winter, thus reducing the heating load, and cooled in summer, thus reducing the cooling load (3-11). The temperature of the air at the exit, like that at the entrance, oscillates above and below the mean annual temperature but the amplitude of the temperature change is smaller at the exit.

This problem is subject to analytical treatment if it is assumed that the outside air temperature varies seasonally according to the equation.

$$\theta_o = \theta_o' \cos wt \qquad (4\text{-}09)$$

θ_o = Outside air temperature, deg F, at time, t.

θ_o' = Outside air temperature minus mean annual temperature, deg F, maximum or minimum.

w = Angular velocity, 2π radians per year = 0.000717 radian hr^{-1}

t = Time, hours ($t = o$ when $\theta_o = \theta_o'$)

4-05 Heating or Cooling of Air by Tunnels or Shafts

Fresh or outside air needed for ventilation is often introduced to installations through shafts or tunnels with bare walls so that the air flows in contact with the surrounding rock. For a tunnel in continuous use, heat is alternately transferred from the air to the rock in summer and from the rock to the air in winter. Savings are possible under both conditions since the air is warmed in winter, thus reducing the heating load, and cooled in summer, thus reducing the cooling load (3-11). The temperature of the air at the exit, like that at the entrance, oscillates above and below the mean annual temperature but the amplitude of the temperature change is smaller at the exit.

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θ_o = Outside air temperature, deg F, at time, t.

θ_o' = Outside air temperature minus mean annual temperature, deg F, maximum or minimum

w = Angular velocity, 2π radians per year = 0.000717 radian hr^{-1}

t = Time, hours ($t = o$ when $\theta_o = \theta_o'$)

Based on this assumption, equations yielding results relevant to air conditioning are as follows:

For the temperature at distance L in the tunnel and at time, t,

$$\theta_L = \theta_o' \, e^{-C'C} \cos\,(wt - wL/V - C'B) \qquad (4\text{-}10)$$

Maximum and minimum air temperature at point L; summer and winter design temperatures

$$\theta_L' = \pm\, \theta_o' \, e^{-C'C} \qquad (4\text{-}11)$$

Rate of heat loss or gain by the air in length L at time, t:

$$q = 0.0566\ Va^2\,(\theta_o - \theta_L) \qquad (4\text{-}12)$$

Total heat gain of air in winter (equals total heat loss of air in summer)

$$Q = 157.7\ Va^2\theta_o' \sqrt{1+e^{-C'C} - 2e^{-C'C}\cos\,(wL/V + C'B)} \qquad (4\text{-}13)$$

where A = Average cross section area of airway, ft^2

$a = 2A/P$, hydraulic radius of airway, ft.

$B = f_2\,(z, b)$ (Figure 4-9)

$b = h/K\,\sqrt{a/w}$

$C = f_1\,(z, b)$ (Figure 4-8)

$C' = \dfrac{hL}{Va}$

e = Base of natural logarithms

h = Coefficient of heat transfer between the moving air and the surface of airway, Btu $hr^{-1}ft^{-2}F^{-1}$

K = Thermal conductivity of rock, Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$

L = Distance from outside entrance of airway, ft.

P = Average perimeter of airway, ft.

T = Period, 8760 hr (1 year)

V = Velocity of air stream, ft hr^{-1}

w = Angular velocity, $2\pi/T$ = 0.000717 radians hr^{-1}

$z = a\sqrt{w/\alpha}$

α = Thermal diffusivity ft^2hr^{-1}

θ = Departure of temperature from the mean annual temperature, F; θ', maximum departure or amplitude; θ_o, outside air; θ_L, at distance L in airway

B, C, and Equations 4-12 and 4-12 are based on the assumption that the density and specific heat of air are 0.075 lb ft^{-3} and 0.018 Btu $ft^{-3}F^{-1}$, respectively.

Form F is suggested as a work sheet for problems of this type. If a tunnel or shaft is used intermittently as an airway, the equations in this section do not apply without modification and the effects of such an airway cannot be estimated unless the method of using it is stated.

Values of h, the surface film coefficient of heat transfer for various values of V, the air velocity, in the tunnel or shaft are given on figure 4-10.

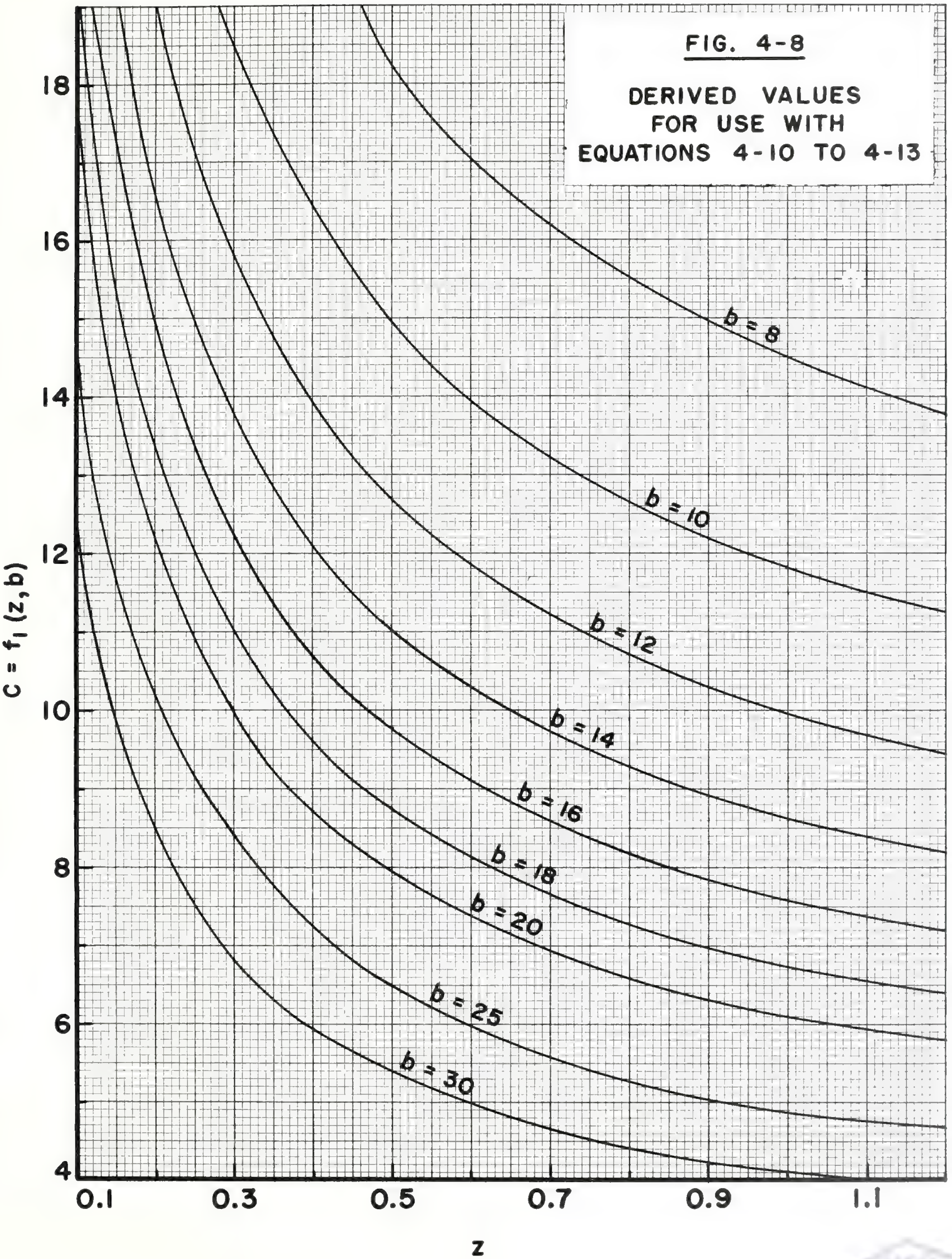
FIG. 4-8
DERIVED VALUES
FOR USE WITH
EQUATIONS 4-10 TO 4-13
C = f1 (z,b)
z
18
16
14
12
10
8
6
4
0.1
0.3
0.5
0.7
0.9
1.1
b = 8
b = 10
b = 12
b = 14
b = 16
b = 18
b = 20
b = 25
b = 30

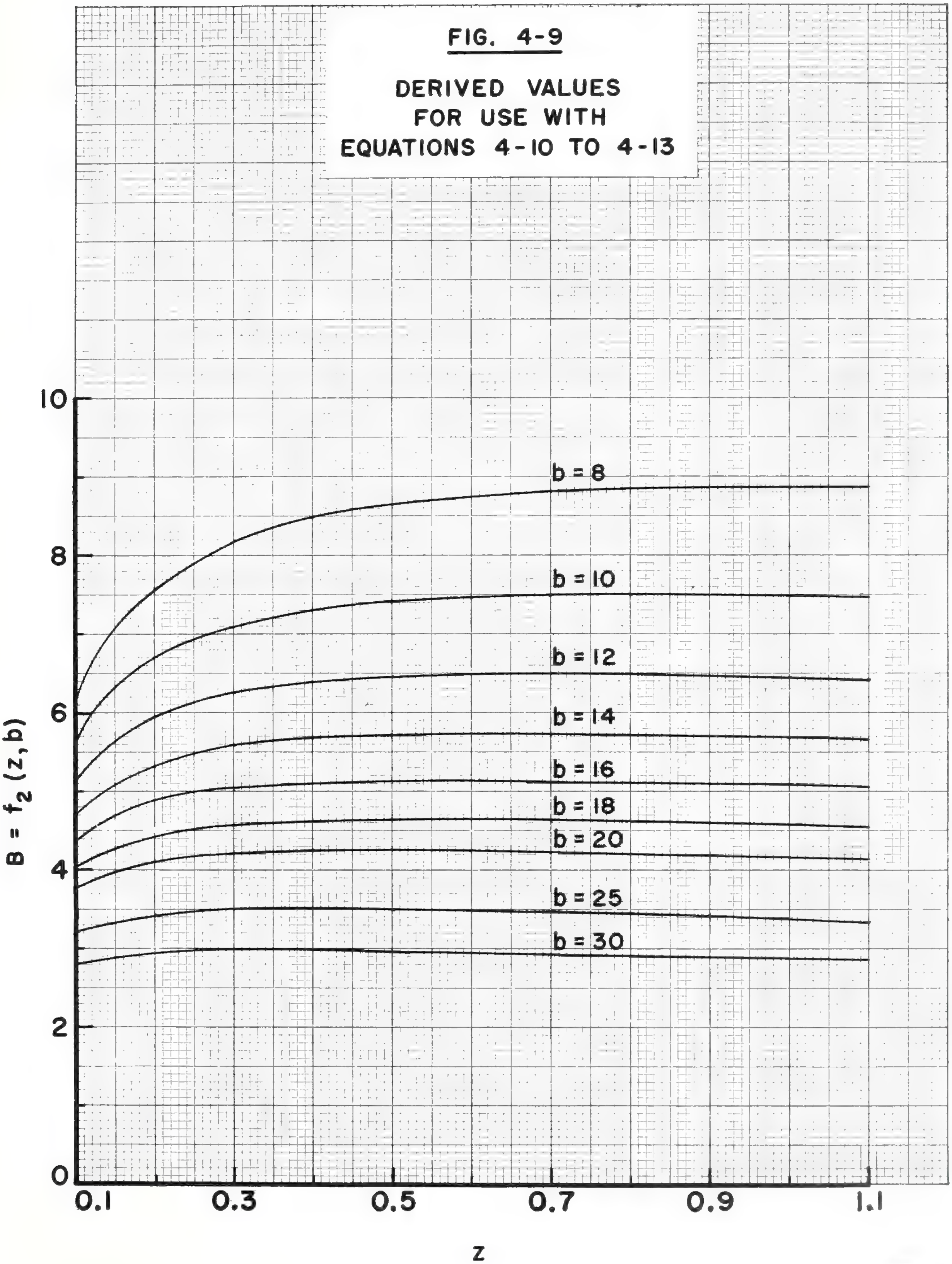

FIG. 4-9

DERIVED VALUES FOR USE WITH EQUATIONS 4-10 TO 4-13

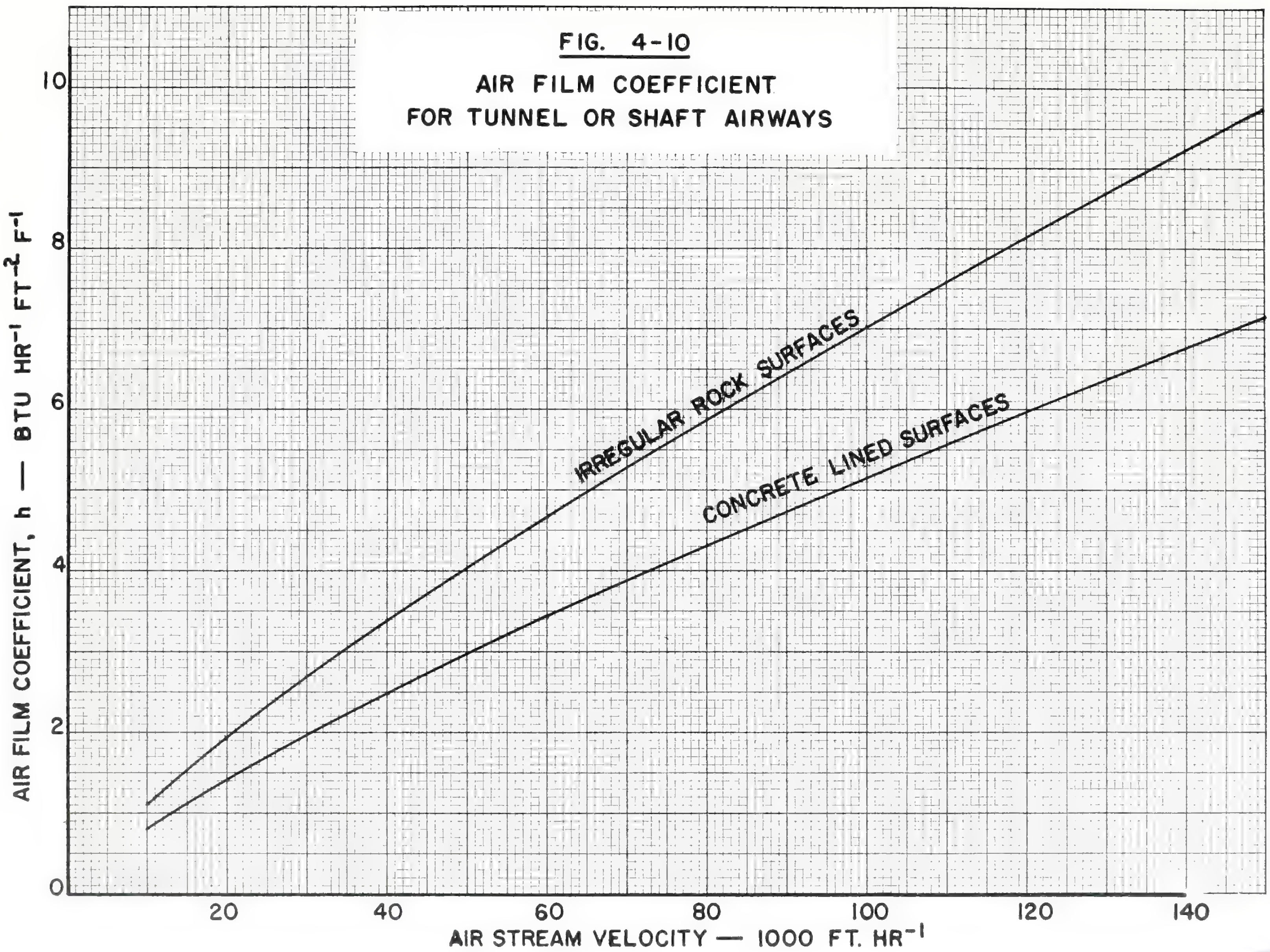

FIG. 4-10

AIR FILM COEFFICIENT
FOR TUNNEL OR SHAFT AIRWAYS

4-06 Thermal Properties of Rock

Rock heat absorption computations depend on the thermal properties of the rock and it is unfortunate that the available data are incomplete and, in some degree, discordant. For estimating purposes it is recommended that a specific heat of 0.2 Btu $lb^{-1}F^{-1}$ be assumed for any rock and for use in the equations in this chapter although rock specific heats as low as 0.16 Btu $lb^{-1}F^{-1}$ have been reported.

For greenstone, present in the mountains of Virginia, tests and experience show a thermal conductivity of about 1.5 Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$, with a density of 186 lbs ft^{-3}. These figures have been used in demonstration problems in connection with this work and are regarded as good assumptions at least for preliminary estimates in many cases. When precision is required, however, more precise values can be obtained either by testing some specimens for conductivity or by the use of figure 4-11 in conjunction with a petrographic analysis of some specimens. Facilities for making these tests or analyses are maintained in several laboratories in this country.

For igneous and metamorphic rocks the density generally falls in the range from 150 to 190 lbs ft^{-3}, and that of the sedimentary rocks in the range from 100 to 175 lbs ft^{-3}. For igneous and metamorphic rocks, the thermal conductivity falls in a range from 1.2 to 2.0 Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$.

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For greenstone, present in the mountains of Virginia, tests and experience show a thermal conductivity of about 1.5 Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$, with a density of 165 lbs ft^{-3}. These figures have been used in demonstration problems in connection with this work and are regarded as good assumptions at least for preliminary estimates in many cases. When precision is required, however, more precise values can be obtained either by testing some specimens for conductivity or by the use of figure 4-11 in conjunction with a petrographic analysis of some specimens. Facilities for making these tests or analyses are maintained in several laboratories in this country.

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Granites are found to be in the range 20-40 percent quartz, 50-73 percent feldspar and 5-12 percent mafic. The factors which determine the thermal conductivity of sedimentary rocks are numerous; composition, porosity, temperature, grain size and shape, and fluid content all have to be considered.

4-07 Initial Underground Conditions

At depths of 50 to 70 feet, the temperature of earth or rock can be expected to approximate the mean annual temperature for a region in the absence of disturbing factors such as underground fires or large subterranean streams. At greater depths, the temperature is found to be higher, increasing at the rate of about 1F per hundred feet. Earth temperatures thus determined are regarded as adequate for air conditioning estimates for underground spaces although a check of the figures is desirable during the survey of any proposed site.

The earth's surface is warmed chiefly by solar radiation and it is cooled by wind, rain or snow and by radiation to the sky, particularly at night. There is therefore an approximately regular diurnal cycle in the surface temperature but its effect disappears, practically speaking, at a depth of a foot or so in the earth. The annual surface temperature variation is greater and its effects may be significant to depths of 15 or more feet for some purposes. Some measurements were made at various depths down to 13 feet near

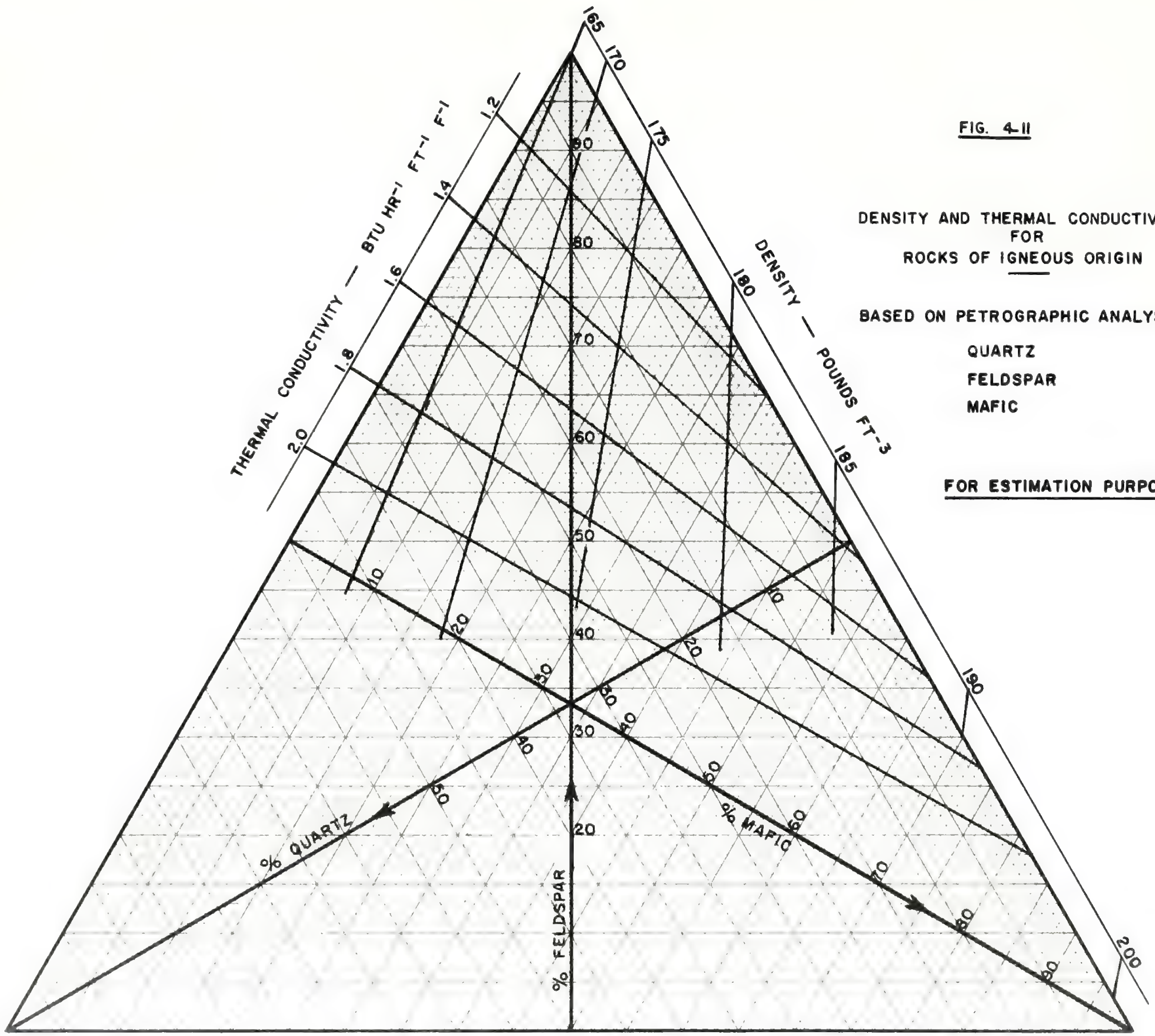

FIG. 4-II

DENSITY AND THERMAL CONDUCTIVITY
FOR
ROCKS OF IGNEOUS ORIGIN

BASED ON PETROGRAPHIC ANALYSIS:

QUARTZ
FELDSPAR
MAFIC

FOR ESTIMATION PURPOSES ONLY

Values of U and of U' for some materials and structures are given in table 4-1 for illustration and possible use in heat transfer estimates. The fact that particular materials and constructions are mentioned in the table is not a recommendation that these materials or constructions should be used. The designing engineer may select other materials in which case suitable values for the coefficients should be otherwise determined.

For a rock surface such as that left after blasting, the surface air film heat transfer coefficient averaged $h = 1.4$ Btu $hr^{-1}ft^{-2}F^{-1}$ in some tests in an underground chamber with only natural air motion. This figure is based on projected wall area, ignoring irregularities left after blasting. For the surface conductances of interior structures, a value of $f_o = f_i = 1.65$ is recommended for present purposes. With these values, heat transfer coefficients of walls, ceilings and floors of interior structures can be computed by means of the following equations:

$$U_o = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.65}} \qquad (4\text{-}14)$$

$$U' = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.25}} \qquad (4\text{-}15)$$

C = Conductance of wall, ceiling or floor of interior structure

TABLE 4-1

Heat Transfer Coefficients for Underground Structures

Material or Structure	U_o	U'
Bare rock surface		1.40
Studs with 3/8" gypsum board on one side	0.67	0.59
Studs with 3/8" gypsum board on both sides	0.37	0.35
Studs with 1/2" insulating board on one side	0.36	0.34
Studs with 1/2" insulating board on both sides	0.19	0.18
Brick, one course - 4" thick no finish	0.60	0.54
Brick, one course - 4" thick 3/8" gypsum bd.	0.51	0.47
Brick, one course - 4" thick 1/2" insulating bd.	0.32	0.30
Brick, two course 8" thick, no finish	0.41	0.38
Concrete, 8" thick, no finish	0.54	0.49
Concrete construction floors, (3") no ceiling, no flooring	0.68	0.60
Concrete construction floors, (3") no ceiling, 1/8" asphalt tile	0.66	0.59
Metal roof deck, bare	0.90	0.77
Metal roof deck, roofing and 1/2" insulating board	0.33	0.31
Wood roof 1" roofing and 1/2" insulating bd.	0.25	0.24

U_o = heat transfer coefficient, based on temperature difference between air in conditioned space and air outside, in the annular space, with zero wind.

U' = heat transfer coefficient, Btu per hour for each square foot of rock surface area and for each degree F difference in temperature between rock surface and air in conditioned spaces.

4-09 Vapor Permeability of Materials

A vapor barrier material may sometimes be included in the walls, ceiling or floor of an internal structure to reduce the latent air conditioning load or to preclude harmful condensation inside the wall, ceiling or floor construction. The danger of condensation in parts of an underground structure is not considered great particularly if the space is continuously air conditioned because the temperature differences or gradients are not severe compared to these that occur in surface buildings. Data are lacking but it appears that condensation might occur in a construction such as a double-faced wall containing insulation. A vapor barrier might therefore be installed in or near the outer surface as precautionary measure.

A method for predicting vapor transfer and condensation in walls is presented in "Moisture Condensation in Building Walls" (ref. 17) with some data on the permeabilities of some materials used in buildings. The method is based on the theory that water vapor transfer through a material is proportional to vapor pressure difference between the two sides and that resistances are additive as they are for heat flow. It is known that this is only an approximation but it may be close enough for practical estimating purposes. Another uncertainty in this field concerns the vapor permeance of materials which differs considerably

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between specimens of the same material. However, the data in Table 4-2 were selected to show the range of the permeances of some materials used in buildings as observed by Babbitt (a) and Teesdale (b), reported in Reference 17.

TABLE 2

Permeance of Some Materials to Water Vapor

Material	Thickness Inches	Permeance P	Resistance (1/P)
Wood - spruce	(a) 0.563	3.48	0.287
Wood - pine	(a) 0.645	2.52	.397
Paper, kraft, 1 sheet	(a) 0.004	168.00	.004
Asphalt felt, 15-lb., dull surface	(a) 0.032	13.50	.074
Asphalt-coated paper, 50 lb	(a) -	1.04	.962
Plasterboard, between heavy sheets of paper	(a) 0.37	70.20	.014

Unit of permeance, P = 1 grain $ft^{-2}hr^{-1}(lb/in^2)^{-1}$ (Permeance in perms = 0.49 P)

4-10 Underground Water

In damp regions or seasons water may enter an underground chamber in either of two ways. It may soak through pervious rock and appear as dampness on the surface, perhaps with streams running or dripping downward, or it may leak in

through faults or fissures. At the greater depths, entrance of water through fissures, rather than through pervious rock, is usual because a site in hard rock is likely to be chosen, if possible, for structural strength. Such rock is likely to be impervious or nearly so. Because the possible hydrostatic pressures are high (3-08) it is customary to drain off excess water rather than attempt to stop the leaks or to treat the rock surface and make it impervious.

Evaporation from rock surfaces may have significant effect on the humidity in bare chambers. When such a chamber is first warmed, the rock can act as a dehumidifier and tend to hold the dewpoint at the surface temperature. In the course of time, the rock surface temperature increases and water evaporating from the surface becomes part of the latent load. Figure L-13 is a means of estimating the evaporation from wet or damp surfaces, based on data in reference 18. The curve gives the average rate of evaporation, M^1, in lb $hr^{-1}ft^{-2}$ for a wet surface L ft long in the direction of air flow parallel to the surface for a velocity of V ft min^{-1} and for a vapor pressure difference (Ps-Pa) psi, where Ps is the vapor pressure of water at the temperature of the wet surface, and Pa is the vapor pressure of the moving air.

Estimates of evaporation from rock are difficult because the area of the wet surface cannot be predicted with certainty for any proposed underground chamber. In the installation so far examined in the eastern United States the wet area did not

through faults or fissures. At the greater depths, entrance of water through fissures, rather than through pervious rock, is usual because a site in hard rock is likely to be chosen, if possible, for structural strength. Such rock is likely to be impervious or nearly so. Because the possible hydrostatic pressures are high (3-10) it is customary to drain off excess water rather than attempt to stop the leaks or to treat the rock surface and make it impervious.

Evaporation from rock surfaces may have significant effect on the humidity in cave chambers. When such a chamber is first warmed, the rock may act as a dehumidifier and tend to hold the dewpoint at the surface temperature. In the course of time, the rock surface temperature increases and water evaporating from the surface becomes part of the latent load. Figure 4-11 is a means of estimating the evaporation from wet or damp surfaces, based on data in reference 111. The curve gives the average rate of evaporation, W', in lb $hr^{-1} ft^{-2}$ for a wet surface L ft long in the direction of air flow parallel to the surface for a velocity of V ft min^{-1} and for a vapor pressure difference $(P_w - P_a)$ in Hg, where P_w is the vapor pressure of water at the temperature of the wet surface, and P_a is the vapor pressure of the moving air.

Estimates of evaporation from rock are difficult because the area of the wet surface cannot be predicted with certainty for any proposed underground chamber. In the installations so far examined in the eastern United States the wet area did not

exceed 10 percent of the total. In the arid regions of the west, dampness on the walls would be rare.

For an internal structure, evaporation from the rock may not be important since the ingress of vapor to the conditioned space can be limited by vapor barriers if necessary; also, if the annular space is used as an exhaust plenum, most of the vapor due to evaporation is carried out by the leaving air. However, materials or equipment such as pipes, ducts, wiring, or timber enclosed in the annular space or in contact with the rock should be capable of withstanding humidities of 100 percent since parts of this space may contain saturated air at times.

If a structure is so arranged that the rock remains cool, at say 55F, while the interior structure is held at some higher temperature, say 75F and 50 percent humidity, the rock can serve as a condenser and assist in dehumidifying the structure. In this case the vapor barrier is not needed. This effect can be useful during emergency periods with arrangements suitably designed to employ it. In this case either dampness or free water in the annular space, being drained away, has no objectionable effects since evaporation does not occur from the surface.

Metals and metal foils are practically perfect vapor barriers except for possible leaks at joints. If leaks exist in any vapor barriers the resulting vapor transfer by convection

exceed 10 percent of the total. In the arid regions of the west, dampness on the walls would be rare.

For an internal structure, evaporation from the rock may not be important since the ingress of vapor to the conditioned space can be limited by vapor barriers if necessary also. If the annular space is used as an exhaust plenum, most of the vapor due to evaporation is carried out by the leaving air. However, materials or equipment such as pipes, ducts, wiring, or timber enclosed in the annular space or in contact with the rock should be capable of withstanding humidities of 100 percent since parts of this space may contain saturated air at times.

If a structure is so arranged that the rock remains cool, at say [illegible], while the interior structure is held at some higher temperature, say [illegible] and [illegible] percent humidity, the rock can serve as a condenser and assist in dehumidifying the structure. In this case the vapor barrier is not needed. This effect can be useful during emergency periods with arrangements suitably designed to employ it. In this case either dampness or free water in the annular space, being drained away, has no objectionable effects since evaporation does not occur from the surface.

Rubble and metal walls are practically without vapor barriers except for possible leaks at joints. [illegible] in any vapor barriers the resulting vapor transfer by convection

can readily exceed the effect of permeability of materials or diffusion and convection cannot be predicted since it depends on quality of workmanship.

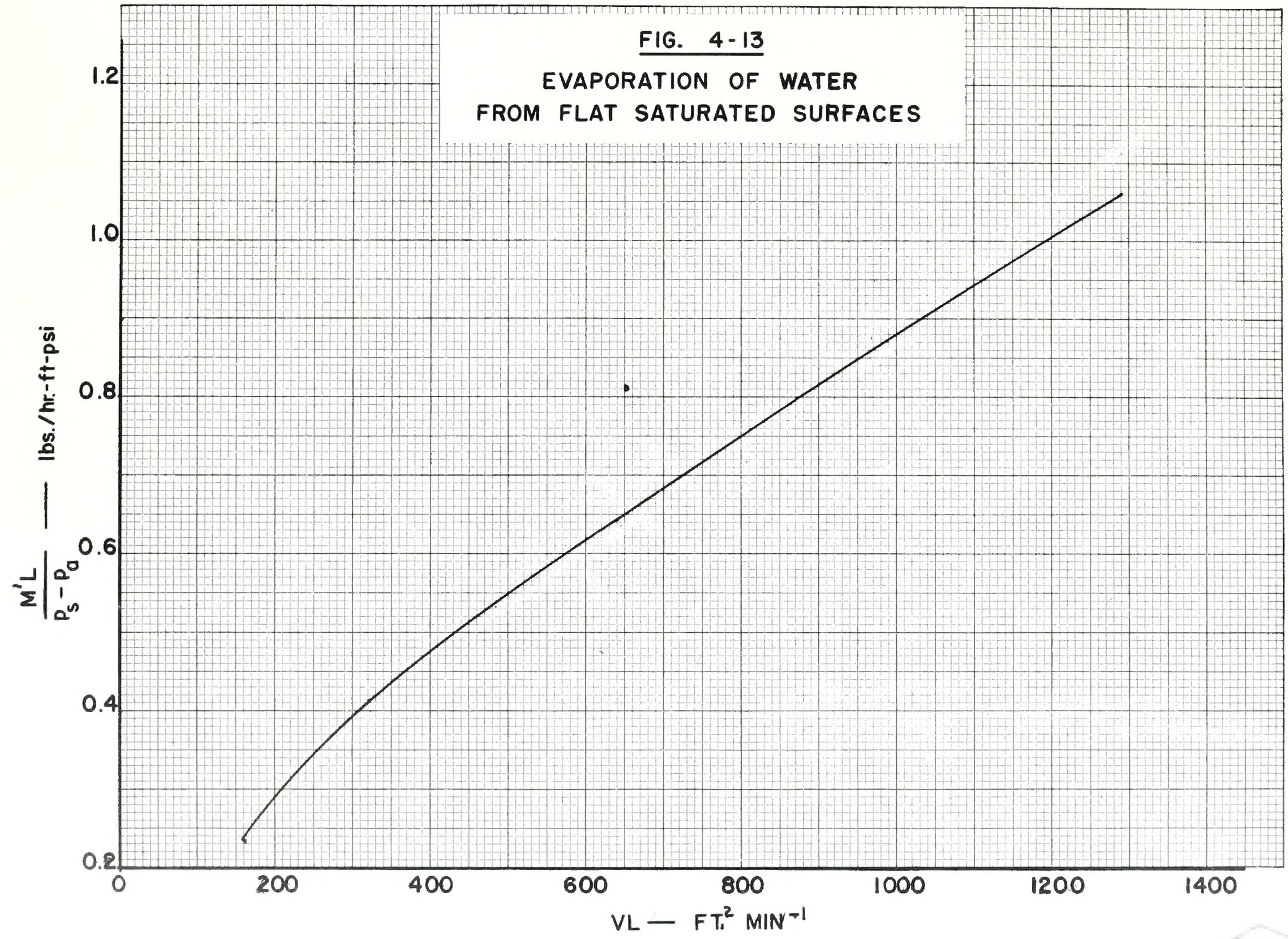

FIG. 4-13
EVAPORATION OF WATER
FROM FLAT SATURATED SURFACES
1.2
1.0
0.8
0.6
0.4
0.2
$\frac{M'L}{P_s - P_a}$ — lbs./hr.-ft-psi
0
200
400
600
800
1000
1200
1400
VL — FT.^{2} MIN^{-1}

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